A NEW STATE-SPACE MODEL OF THREE-PHASE POWER SYSTEMS: APPLICATION IN POSITIVE AND NEGATIVE SEQUENCE ESTIMATION

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ABSTRACT

Power quality is drawing much concern recently. In order for monitor power quality of power systems in real time, numerous modelling of power signals (voltages and/or currents) has been proposed to estimate the parameters of the systems. Unfortunately, most of the models fail to completely represent most important characteristics of the signals of a three-phase power system. This paper proposes a new state-space model that can well represent a real three-phase power system by taking into account the unbalance conditions and harmonic distortion of a three-phase power system. The model associated with Extended Kalman Filter is then applied to estimate the positive and negative sequences of the fundamental component. The simulation results show that the proposed approach can accurately estimate the sequences of a three-phase power system in real time.

Keywords: *State space model;Unbalance; Harmonic; Extended Kalman Filter.*

TÓM TẮT

Chất lượng điện năng là chủ đề nghiên cứu thu hút nhiều sự quan tâm gần đây. Để giám sát chất lượng điện năng của hệ thống điện, nhiều mô hình tín hiệu điện (điện áp/dòng điện) đã được đề xuất để ước lượng các tham số của hệ thống điện. Vậy nhưng, hầu hết những mô hình này không thể mô tả đầy đủ các đặc điểm quan trong của tín hiệu điện của hệ thống điện ba pha. Bài báo này đề xuất một mô hình mới biểu diễn một hệ thống điện ba pha thực tế trên không gian trạng thái, trong đó mô tả cả hiện tượng mất cân bằng và hiện tượng sóng hài của hệ thống điện ba pha. Mô hình trạng thái này được áp dụng với bộ lọc Kalman mở rộng để ước lượng các thành phần thứ tự thuận và thứ tự nghịch của thành phần tần số cơ bản trong tín hiệu điện ba pha. Kết quả mô phỏng chỉ ra rằng phương pháp được đề xuất trong bài báo có thể ước lượng chính xác các thành phần thứ tự thuận và thứ tự nghịch này.

Từ khóa: *Mô hình trạng thái; Mất cân bằng; Sóng hài; Bộ lọc Kalman mở rộng.*

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Ngày nhận bài: 01/11/2018
Ngày nhận bài sửa sau phản biện: 15/12/2018
Ngày chấp nhận đăng: 25/02/2019

SYMBOL

Symbol	Unit	Meaning
T_s	s	Sample time
v_a, v_b, v_c	V	a phase voltage, b phase voltage, c phase voltage

1. INTRODUCTION

In ideal three-phase power systems, the three-phase currents/voltages should be constant-frequency sinusoids with equal magnitudes and phases-shifted by 120^0. Such three-phase power systems are balanced systems [1]. Unfortunately, in practice because of uneven distribution of single-phase load, asymmetrical faults or other reasons, the power systems become unbalanced, i.e., the three-phase currents/voltages are often different in magnitudes and/or their phases are not 120^0 apart. Additionally, due to load and power supply variation, the fundamental frequency and the voltages' amplitudes of a three-phase power system are not constant but changing in time [2, 3]. Because of the appearance of nonlinear loads, power signals are also contaminated by high-order frequencies sinusoids called harmonics. The frequency values of harmonics are multiples of the fundamental frequency [4]. These power quality problems affect the reliability and stability of power systems and must be identified as fast as possible [5].

In order to effectively monitor three-phase power systems' operating conditions, various models of three-phase power systems have been proposed to estimate their parameters. [6] proposed a state-space model of three-phase voltages. However, the model assumes the systems to be balanced and ignores the unbalance characteristics. Comparing to [6], the state-space model presented in [7] can represent an unbalanced system by introducing one more state variable. Nevertheless, it ignored the existence of high-order frequency sinusoids in the three-phase voltages/currents. The state-space model in [8] already considered the unbalance condition and harmonic distortion of a three-phase power system, nevertheless, it requires the fundamental frequency to be provided. Similarly, Multi-output Adaline [9] also needs to know the value of the fundamental frequency in advance.

Symmetrical theory provides an effective solution to analyze an unbalanced power system by breaking down the unbalance voltage/current into three balanced systems: the positive, the negative and the zero sequence [10]. The negative sequence is useful indication of unbalanced systems and used in fault detection, fault location and overcurrent detection [11, 12]. On the other hand, the positive-sequence quantity is needed in evaluating voltage variation of power systems which is significant to monitor and control the systems' stability [8].

This research proposes a new state-space model that can describe the unbalance, the harmonic contamination and the unknown fundamental frequency of a three-phase power system. Then Extended Kalman Filter is applied on this model to estimate the positive and negative sequence of the fundamental components including their amplitudes and phases. The organization of this paper is as follows. In Section 2, the state-space model in [7] are presented. This model ignores the existence of harmonics in power signals. Based on this model, in Section 3, a new state-space model is introduced considering the appearance of harmonic components. An identification scheme to estimate the state variables of the new model is also proposed in this section. Section 4 describes the application of the new approach in estimating the positive and negative sequences of the fundamental component. Section 5 presents simulation results of the performance of the proposed model associated with Extended Kalman Filter. Section 6 concludes the paper.

2. REVIEW OF THE STATE-SPACE MODEL OF THREE-PHASE POWER SYSTEMS [7]

In this section, the state-space model of unbalanced three-phase voltages and/or currents in [7] will be presented. Consider unbalanced three phase voltages of the following expression:

$$\begin{cases} v_a(k) = V_a \sin(\omega k T_s + \phi_a) \\ v_b(k) = V_b \sin(\omega k T_s + \phi_b) \\ v_c(k) = V_c \sin(\omega k T_s + \phi_c) \end{cases} \quad (1)$$

where k is the iteration number, T_S is the sampling period, V_a, V_b, V_c are the amplitudes, $f = \frac{\omega}{2\pi}$ is the fundamental frequency, ϕ_a, ϕ_b, ϕ_c are the initial phase angles of the three-phase voltages.

In [10], the set of three phase signals can be represented as a sum of three sets according to the theory of symmetrical components:

$$\begin{bmatrix} v_a(k) \\ v_b(k) \\ v_c(k) \end{bmatrix} = \begin{bmatrix} v_a^+(k) \\ v_b^+(k) \\ v_c^+(k) \end{bmatrix} + \begin{bmatrix} v_a^-(k) \\ v_b^-(k) \\ v_c^-(k) \end{bmatrix} + \begin{bmatrix} v_a^o(k) \\ v_b^o(k) \\ v_c^o(k) \end{bmatrix} \quad (2)$$

In (2), the set:

$$\begin{cases} v_a^+(k) = V_+ \sin(\omega k T_s + \phi_+) \\ v_b^+(k) = V_+ \sin(\omega k T_s + \phi_+ - \frac{2\pi}{3}) \\ v_c^+(k) = V_+ \sin(\omega k T_s + \phi_+ + \frac{2\pi}{3}) \end{cases} \quad (3)$$

is the positive sequence, that has clockwise rotation of a-b-c. V_+ and $\varphi_+ = \omega k T_s + \phi_+$ are respectively the amplitude and phase angle of this positive sequence.

Additionally, the set:

$$\begin{cases} v_a^-(k) = V_- \sin(\omega k T_s + \phi_-) \\ v_b^-(k) = V_- \sin(\omega k T_s + \phi_- + \frac{2\pi}{3}) \\ v_c^-(k) = V_- \sin(\omega k T_s + \phi_- - \frac{2\pi}{3}) \end{cases} \quad (4)$$

is the negative sequence that has counter-clockwise rotation of a-b-c. V_- and $\varphi_- = \omega k T_s + \phi_+$ are respectively the amplitude and phase angle of this negative sequence.

Finally the set

$$\begin{cases} v_a^o(k) = V_o \sin(\omega k T_s + \phi_0) \\ v_b^o(k) = V_o \sin(\omega k T_s + \phi_0) \\ v_c^o(k) = V_o \sin(\omega k T_s + \phi_0) \end{cases} \quad (5)$$

is the zero sequence of three phases with the same magnitude and in phase.

Applying Clark's transform [10] to transform the positive sequence in three dimensional coordinate to two dimensional αβ coordinate:

$$\begin{bmatrix} v_\alpha^+(k) \\ v_\beta^+(k) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a^+(k) \\ v_b^+(k) \\ v_c^+(k) \end{bmatrix} \quad (6)$$

results in:

$$\begin{cases} v_\alpha^+(k) = V_+ \cos(\omega k T_s + \phi_+) \\ v_\beta^+(k) = V_+ \sin(\omega k T_s + \phi_+) \end{cases} \quad (7)$$

The complex form of the positive sequence is determined as:

$$v^+(k) = v_\alpha^+(k) + j v_\beta^+(k) = A_+ e^{j\omega k T_s} \quad (8)$$

with $A_+ = V_+ e^{j\phi_+}$

Similarly, the Clark's transform of the negative components is:

$$\begin{cases} v_{\alpha}^{-}(k) = V_{-}\cos(\omega kT_s + \phi_{-}) \\ v_{\beta}^{-}(k) = V_{-}\sin(\omega kT_s + \phi_{-}) \end{cases} \tag{9}$$

The complex form of the negative component is calculated from (9) as:

$$v^{-}(k) = v_{\alpha}^{-}(k) + jv_{\beta}^{-}(k) = A_{-}e^{-j\omega kT_s} \tag{10}$$

with $A_{-} = V_{-}e^{j\phi_{-}}$

Through Clark's transform, the zero sequence is eliminated.

By applying Clark's transform on the three phase signals in (1), the resulting complex form of the three phase signals is the sum of the complex currents corresponding to the positive, negative and zero sequences that is:

$$v(k) = V_{+}e^{j\omega kT_s} + V_{-}e^{-j\omega kT_s} \tag{11}$$

(11) can be re-expressed as:

$$v(k) = A_{+}e^{j\omega T_s}e^{j\omega(k-1)T_s} + A_{-}e^{-j\omega T_s}e^{-j\omega(k-1)T_s} \tag{12}$$

By defining:

$$\begin{cases} q_2(k) = A_{+}e^{j\omega kT_s} \\ q_3(k) = A_{-}e^{j\omega kT_s} \end{cases} \tag{13}$$

and by assuming the fundamental frequency of system (1) is constant in one sampling period, the following equations can be deduced from (13):

$$\begin{bmatrix} q_2(k+1) \\ q_3(k+1) \end{bmatrix} = \begin{bmatrix} e^{j\omega T_s}q_2(k) \\ (e^{j\omega T_s})^{-1}q_3(k) \end{bmatrix} \tag{14}$$

If frequency ω in (1) is unknown, $e^{j\omega T_s}$ is considered an unknown parameter of model (14). Let $q_1(k) = e^{j\omega T_s}$, the following model contains three state variables $q_1((k)$, $q_2(k)$, $q_3(k)$:

$$\begin{bmatrix} q_1(k+1) \\ q_2(k+1) \\ q_3(k+1) \end{bmatrix} = \begin{bmatrix} q_1(k) \\ q_1(k)q_2(k) \\ q_1(k)q_3(k) \end{bmatrix} \tag{15}$$

with a scalar output:

$$y(k) = v(k) = \begin{bmatrix} 0 & 1 & 1 \end{bmatrix}\begin{bmatrix} q_1(k) & q_2(k) & q_3(k) \end{bmatrix}^T \tag{16}$$

Model (15), (16) is a nonlinear state space model. Although this model takes into account unbalance conditions of power systems, it does not consider high-frequency harmonics which are prevail in the signals of power systems. Therefore, this model is insufficient to represent a practical three-phase power system and if used to estimate the fundamental frequency and the positive and negative sequences of unbalanced three-phase voltages under harmonic distortion, the estimation results will be less accurate due to model error.

3. PROPOSAL OF A NEW STATE-SPACE MODEL OF THREE-PHASE SYSTEMS AND ITS ASSOCIATED IDENTIFICATION SCHEME

3.1. A new state-space model of unbalanced three-phase systems in harmonic distortion

According to [10], the three-phase voltages (or currents) of an unbalanced three-phase power system under harmonic distortion are described as:

$$\begin{cases} v_a(k) = \sum_n V_{na}\sin(n\omega kT_s + \phi_{na}) \\ v_b(k) = \sum_n V_{nb}\sin(n\omega kT_s + \phi_{nb}) \\ v_c(k) = \sum_n V_{nc}\sin(n\omega kT_s + \phi_{nc}) \end{cases} \tag{17}$$

where n is harmonic order; V_{na}, V_{nb}, V_{nc} and $\phi_{na}, \phi_{nb}, \phi_{nc}$ are correspondingly the amplitudes and initial phase angles of the three-phase order-n harmonic.

In order to modelling the three-phase voltages v_a, v_b, v_c, this proposal applies the modelling method in the previous section to get the state-space model of each three-phase harmonic (the fundamental term can be considered as harmonic order 1).

$$\begin{cases} V_{na}\sin(n\omega kT_s + \phi_{na}) \\ V_{nb}\sin(n\omega kT_s + \phi_{nb}) \\ V_{nc}\sin(n\omega kT_s + \phi_{nc}) \end{cases} \tag{18}$$

with n = 1, 2, 3,... A combination of all the harmonic models gives the complete state-space model of (17).

For simplicity, consider three-phase voltages with harmonics order n = 3 and n = 5 as follows:

$$\begin{cases} v_a(k) = V_{1a}\sin(\omega kT_s + \phi_{1a}) + V_{3a}\sin(3\omega kT_s + \phi_{3a}) \\ \qquad + V_{5a}\sin(5\omega kT_s + \phi_{5a}) \\ v_b(k) = V_{1b}\sin(\omega kT_s + \phi_{1b}) + V_{3b}\sin(3\omega kT_s + \phi_{3b}) \\ \qquad + V_{5b}\sin(5\omega kT_s + \phi_{5b}) \\ v_c(k) = V_{1c}\sin(\omega kT_s + \phi_{1c}) + V_{3c}\sin(3\omega kT_s + \phi_{3c}) \\ \qquad + V_{5c}\sin(5\omega kT_s + \phi_{5c}) \end{cases} \tag{19}$$

As in Section 2, the fundamental components:

$$\begin{cases} V_{1a}\sin(\omega kT_s + \phi_{1a}) \\ V_{1b}\sin(\omega kT_s + \phi_{1b}) \\ V_{1c}\sin(\omega kT_s + \phi_{1c}) \end{cases} \tag{20}$$

are represented by two state variables $q_2(k)$ and $q_3(k)$ with the following equations:

$$\begin{bmatrix} q_2(k+1) \\ q_3(k+1) \end{bmatrix} = \begin{bmatrix} e^{j\omega T_s}q_2(k) \\ (e^{j\omega T_s})^{-1}q_3(k) \end{bmatrix} \tag{21}$$

where $e^{j\omega T_s}$ is an unknown parameter.

Similarly, the 3rd order harmonics are represented by two state variables $q_4(k)$ and $q_5(k)$ such that:

$$\begin{bmatrix} q_4(k+1) \\ q_5(k+1) \end{bmatrix} = \begin{bmatrix} (e^{j\omega T_s})^3 q_4(k) \\ (e^{j\omega T_s})^{-3} q_5(k) \end{bmatrix} \quad (22)$$

And the 5th order harmonics are described by two state variables

$$\begin{bmatrix} q_6(k+1) \\ q_7(k+1) \end{bmatrix} = \begin{bmatrix} (e^{j\omega T_s})^5 q_6(k) \\ (e^{j\omega T_s})^{-5} q_7(k) \end{bmatrix} \quad (23)$$

From (21) (22) (23), the model of the three phase voltages (19) is:

$$\begin{cases} q_2(k+1) = e^{j\omega T_s} q_2(k) \\ q_3(k+1) = (e^{j\omega T_s})^{-1} q_3(k) \\ q_4(k+1) = (e^{j\omega T_s})^3 q_4(k) \\ q_5(k+1) = (e^{j\omega T_s})^{-3} q_5(k) \\ q_6(k+1) = (e^{j\omega T_s})^5 q_6(k) \\ q_7(k+1) = (e^{j\omega T_s})^{-5} q_7(k) \end{cases} \quad (24)$$

where $e^{j\omega T_s}$ is an unknown parameter. By introducing one more state variable $q_1(k) = e^{j\omega T_s}$, model (24) becomes:

$$\begin{cases} q_1(k+1) = q_1(k) \\ q_2(k+1) = q_1(k) q_2(k) \\ q_3(k+1) = q_1(k) q_3(k) \\ q_4(k+1) = q_1^3(k) q_4(k) \\ q_5(k+1) = q_1^{-3}(k) q_5(k) \\ q_6(k+1) = q_1^5(k) q_6(k) \\ q_7(k+1) = q_1^{-5}(k) q_7(k) \end{cases} \quad (25)$$

The model's output y(k) is set as the complex form of the three phase voltages $v_a(k)$, $v_b(k)$, $v_c(k)$ in (19) which is sum of the complex forms of all the harmonics of the three-phase voltages as follows:

$$y(k) = [0\,1\,1\,1\,1\,1\,1]\left[q_1(k) q_2(k) q_3(k) q_4(k) q_5(k) q_6(k) q_7(k)\right]^T \quad (26)$$

Since $v_a(k)$, $v_b(k)$, $v_c(k)$ are measured from the grid, y(k) can be determined from the voltages at each iteration k. Among the state variables of (25) and (26), $q_1(k)$ represents the fundamental frequency and the others correspondingly represent the positive and negative sequences of the fundamental and the harmonics. If more other harmonic orders appear in (19), more state variables can be added to (25) and (26) to represent these harmonics.

Model (25 and (26) can be used with an identification scheme to estimate the states of power systems.

3.2. Identification scheme:

Kalman Filter is an iterative identification method for identifying the state variables of linear state-space models [13]. Extended Kalman Filter is an extension of Kalman Filter for nonlinear state-space models [13]. Since model (25), (26) is a non-linear state-space model, in this paper, Extended Kalman Filter [13] is chosen as the identification scheme to associate with the proposed model to estimate its state variables. However, the methods based on Extended Kalman Filter have to deal with the difficulty of choosing initial values of the state variables in order to prevent the estimation from bias and divergence [13, 14]. Hereafter, we propose a solution to solve the initialization problem of the proposed method.

The real frequency should deviate around its nominal value (50±0,2Hz, for example) [12]. In addition, recalling that $q_1(k) = e^{j\omega T_s}$, a small sampling time T_s makes the difference of the nominal value and the real frequency negligible. If the fundamental frequency is assigned to the nominal value, the state variable $q_1(k)$ becomes a constant, and then model (25), (26) becomes linear. By applying Kalman Filter to that model, the two state variables $q_2(k)$ and $q_3(k)$ can be estimated to a certain accuracy. Using the observations, an initialization stage can be added. The method now includes two stages: Initialization and tracking.

Initialization stage consists in:

– Fixing the fundamental frequency at its nominal value and then applying Kalman Filter to estimate the state variables $q_2(k)$ and $q_3(k)$ of model (25), (26) in a chosen number of iterations with the variable $q_1(k)$ is a constant.

The tracking stage consists in:

– Assigning the estimated state variables in the initialization stage as initial values for the state variables $q_1(k)$, $q_2(k)$, $q_3(k)$ in this stage. Applying the EKF to the nonlinear model (25), (26) to estimate the state variables.

– At each iteration k, calculating the mean square relative error ε(k) which is the average deviation of the estimated output $\hat{y}(k)$ and the output calculated from measurement. If the error is over a predetermined threshold, this means there is a big change in the signals, for example a jump in the signals' amplitudes, and the estimation is out of track. The initialization stage needs to be restarted.

4. APPLICATIONS OF THE NEW APPROACH IN ESTIMATING THE POSITIVE AND NEGATIVE SEQUENCES OF THE FUNDAMENTAL COMPONENT

The positive sequence of the fundamental component is represented by $\hat{q}_2(k)$, hence, its amplitude V_{1+} and phase angle φ_{1+} are deduced from $\hat{q}_2(k)$ as the following formula:

$$\begin{cases} V_{1+}(k) = \sqrt{\dfrac{2}{3}} \left\| \hat{q}_2(k) \right\| \\ \varphi_{1+}(k) = \dfrac{\pi}{2} + \angle \hat{q}_2(k) \end{cases} \quad (27)$$

where $\left\| \hat{q}_2(k) \right\|$ is amplitude of $\hat{q}_2(k)$ and $\angle \hat{q}_2(k)$ is its phase angle.

The positive sequence of the fundamental components can be reconstructed by applying inverse Clark's transform to $\hat{q}_2(k)$ so that:

$$\begin{bmatrix} i_{1a}^{+}(k) \\ i_{1b}^{+}(k) \\ i_{1c}^{+}(k) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \mathrm{Re}(\hat{q}_2(k)) \\ \mathrm{Im}(\hat{q}_2(k)) \end{bmatrix} \tag{28}$$

Similarly, the amplitude V_{1-} and phase angle φ_{1-} of the negative sequence of the fundamental component can be estimated $\hat{q}_3(k)$ from as follows:

$$\begin{cases} V_{1-}(k) = \sqrt{\frac{2}{3}} \left\| \hat{q}_3(k) \right\| \\ \varphi_{1-}(k) = \frac{\pi}{2} - \angle \hat{q}_3(k) \end{cases} \tag{29}$$

where $\left\| \hat{q}_3(k) \right\|$ is amplitude of $\hat{q}_3(k)$ and $\angle \hat{q}_3(k)$ is its phase angle.

The reconstruction of the negative sequence of the fundamental component is carried out as follows:

$$\begin{bmatrix} i_{1a}^{-}(k) \\ i_{1b}^{-}(k) \\ i_{1c}^{-}(k) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \mathrm{Re}(\hat{q}_3(k)) \\ \mathrm{Im}(\hat{q}_3(k)) \end{bmatrix} \tag{30}$$

The positive and negative sequences of the harmonic components can be estimated in the same way as the estimation of the sequences of the fundamental component.

5. RESULTS AND DISCUSSION

A simulation test with Matlab is conducted to confirm the performance of the proposed method in estimating the fundamental frequency and the positive and negative sequences of the fundamental component. In the test, the testing three-phase voltages are of the form (17) that contains of the fundamental component and the harmonic orders 3rd, 5th and 7th. The amplitude of the positive sequence is 1,0V and of the negative sequence is 0,4V. The fundamental frequency of the signals is 50,2Hz. The sampling time T_s is chosen as 0,0005s. The proposed model is composed of nine state variables for modelling the fundamental components and these harmonics and the model of the method in [7] includes three state variables. For the both models, the variable $q_1(k)$ is initialized at $0{,}9877 + 0{,}1564j$ which corresponds to the fundamental frequency 50Hz and the initial values of the other state variables are set to 0. The estimation results are then compared to the estimation by the method in [7].

Figure 1 shows the estimated amplitudes of the positive and negative sequences of the fundamental component by the proposed method compared to the estimation of the method in [6]. It can be seen that the estimation of the proposed method quickly converges to the true value of these amplitudes. In details, the estimated amplitudes take about one half of a cycle to reach an error less than 1%. On the other hand, the estimation of the method in [7] is oscillating around this value after a long convergence time. The oscillation of the estimation of the method in [7] can be explained by the model error which is resulted from without taking into modelling the harmonic components existing in the testing three-phase voltages.

The performance of the proposed method in estimating the amplitudes of the positive and negative sequences is presented in Table 1. According to this table, the estimation converges to the true value of the amplitudes with a high accuracy (the Mean Square Error (MSE) is about 10^{-9}). The evolution of real the positive and negative sequences and their reconstruction with the proposed method is presented in Figure 2 and Figure 3. It can be seen from these figures that after about quarter of a cycle, the reconstructed signals converge to the real ones.

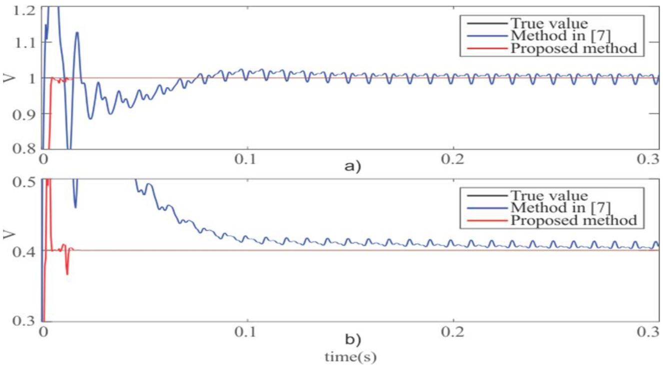

Figure 1. Amplitudes for the positive and negative sequences a) positive sequence b) negative sequence

Table 1. Performance of the proposed method in estimating the amplitudes of the positive and negative sequences

Amplitude	Mean at steady state (V)	MSE at steady state (V)	Error max at steady state (V)
Positive sequence	1.0000	1.1708×10^{-9}	5.2074×10^{-4}
Negative sequence	0.4000	4.8576×10^{-10}	3.9352×10^{-4}

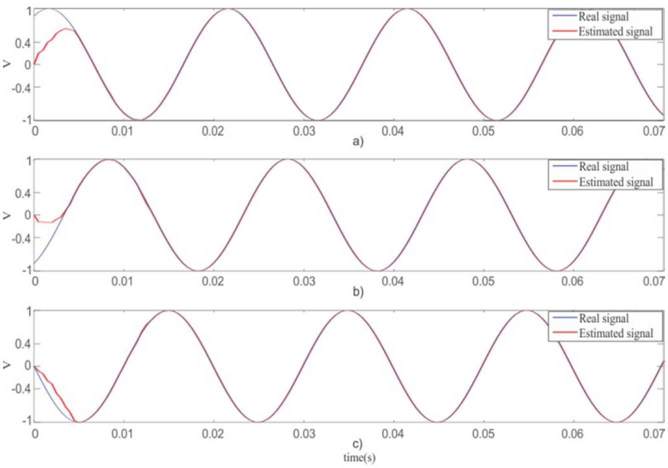

Figure 2. Reconstruction of the positive sequence compared to the real positive sequence a) phase a, b) phase b, c) phase c

6. CONCLUSIONS

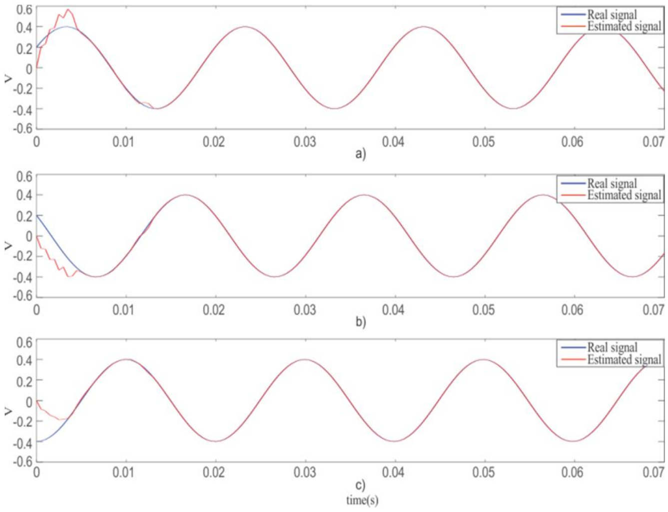

Figure 3. Reconstruction of the negative sequence compared to the real negative sequence a) phase a, b) phase b, c) phase c

In this paper, a new state-space model is presented to modelling the three-phase voltages/currents under unbalance conditions, harmonic distortion with the fundamental frequency unknown. This model is associated with Extended Kalman Filter to estimate the positive and negative sequences of the fundamental component. A simulation is implemented to evaluate the performance of the new proposed method. The simulation results prove that under harmonic distortion and unbalance conditions, the proposed method is efficient in tracking the positive and negative sequence of the fundamental components as well as estimating their amplitudes and phase angles. The application of the proposed method can be extended to fundamental frequency estimation and harmonic estimation of three-phase voltages/currents.

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