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Dynamic Phasor-Based Analysis of Unbalanced Three-Phase Systems in Presence of Harmonic Distortion

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***Abstract*—In this paper, a frequency-based analytical approach for dynamic analyzing of unbalanced three-phase systems in the presence of harmonic distortion using sequence domain is put forward. As will be shown, classical symmetrical components proposed by Fortescue is not applicable under nonsinusoidal periodic condition. In such cases, generalized symmetrical components proposed by Tenti *et al.* can be used to calculate sequences from phase domain values. However, it introduces a new sequence component called residual component, which has a different value for each phase and cannot be directly obtained based on sequence networks. To such aim, using dynamic harmonic domain, an approach that makes it possible to use features of classical symmetrical components and modify the outputs to compute sequences based on the concept of generalized symmetrical components is proposed. Moreover, it is shown that using equivalent circuit for triplen harmonics is essential to find a relation between residual components since if sequences are connected in parallel, it is not possible to modify results of classical symmetrical components and this equivalent circuit should be directly analyzed. Time domain software is used to perform conventional lumped circuit simulation and validate the time domain responses resulted from DHD.**

***Index Terms*—Transient analysis, three-phase unbalanced system, dynamic phasor, symmetrical components.**

I. Introduction

As NON-LINEAR loads in power systems can imply distortion in both current and voltage waveforms. Therefore, it is necessary to investigate the impacts of these distortions on both transient and steady-state responses in unbalanced three-phase systems [1], [2].

Dynamic Phasor (DP) is one of the frequency domain based approaches for dynamic analysis which has been widely applied to modeling of power systems such as electrical machines [3], dynamics and faults of power system [4], [5], Flexible AC Transmission Systems (FACTS) [6], [7], sub-synchronous resonance [8], unbalanced distribution systems [9], and High-Voltage Direct Current (HVDC) systems [10]. In [11], using DP variables instead of instantaneous time variables, a shifted frequency analysis model has been put forward. In [12], application of DP concept has been further extended in two major areas 1) DP modelling of frequency varying systems 2) DP modeling of multi-frequency, multi-generator systems.

The Dynamic Harmonic Domain (DHD) is an extension of DP and can be efficiently used in order to include dynamic analysis of harmonics during transients. The DHD has been applied to FACTS devices, synchronous machines and transformers [13]–[15]. In [16], an extended harmonic domain model of a wind turbine generator system based on doubly fed induction generator has been presented. In addition, a modified harmonic domain, which incorporates interharmonics, has been proposed in [17]. In [18], a major issue about implementation of DHD models has been addressed. It has been shown that spurious oscillations of individual harmonics can be appeared when there is a step change in either input variables or circuit parameters. A new method has been presented for steady and dynamic states harmonic analysis of power systems in [19]. Proposed method employs a decomposition framework in which harmonic sources are considered as separate subsystems which are solved via the DHD method. In [20], an approach to reduce a non-linear system in both harmonics and states, has been proposed which achieves computational time savings while maintaining accuracy. Application of the DHD, to study the effect of the source phase angle on harmonic contents and time domain response during both transient and steady states by defining a phase shift matrix has been presented in [21]. In [22], by using DHD and phase-shifting property of harmonics, it has been shown that a three-phase balanced system (linear or non-linear, supplied by periodic balanced sinusoidal or non-sinusoidal sources) is completely balanced during both transient and steady-state conditions; and single-phase modeling approach has been put forward as the most noteworthy application of the proposed methodology.

Symmetrical components theory for analyzing unbalanced poly-phase networks has been proposed by Fortescue. This method which is frequency-domain based concept, decomposes phasors of unbalanced three-phase system into a group of positive, negative and zero components [23]. However, in [24], it

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has been shown that classical symmetrical components proposed by Fortescue cannot be used in the presence of harmonic unbalance. In fact, as proposed by Tenti *et al.*, classical symmetrical components is a very especial case of a more complete form called generalized symmetrical components. The main conclusion of [24] is that an orthogonal decomposition of periodic non-sinusoidal three-phase signals into positive sequence, negative sequence and zero sequence components is not possible; but that an additional current and voltage component should be introduced which is called residual component. Classical symmetrical component and generalization of the concept of symmetrical component can be derived in both time and frequency domains [24]. However, in [24], phase domain signals are used to determine different sequences and sequence domain is not directly employed to obtain positive, negative, zero and residual sequences.

A review of the literature shows that for harmonic analysis, a symmetric and balanced system is assumed and therefore harmonic calculations are performed considering only positive and negative sequence harmonics. Moreover, considering harmonic distortion, due to drawbacks of classical symmetrical components proposed by Fortescue in [23] and complexity of generalized symmetrical components proposed by Tenti *et al.* in [24], phase domain analysis for calculating *"a"*, *"b"* and *"c"* signals is performed and sequence domain analysis is not directly used. This paper, by using DHD, proposes an approach for dynamic analyzing of unbalanced three-phase systems in the presence of harmonic distortion. It is shown that if multiples of third harmonic are not present in the input sources, results of symmetrical components and those obtained through time domain are in good agreement. However, if multiples of third harmonic are present in the input sources, using classical symmetrical components and time domain solution will not lead to the same results due to presence of residual component in each phase. To such aim, this paper uses the concept of generalized symmetrical components along with equivalent circuit for multiples of third harmonic in order to modify the outputs of classical symmetrical components theory to obtain different sequences under dynamic non-sinusoidal conditions in unbalanced three-phase system.

Paper is organized as follows: Concept of DHD analysis along with phase-shift of periodic signals and generalized symmetrical components are presented in Sections II and III, respectively. Proposed approach of this paper along with problem description have been presented in Sections IV, V and VI.

II. Dynamic Harmonic Domain

The main idea behind the DHD is that a periodical or quasi-periodic function $x(\tau)$ with period of *T*, can be presented by means of complex Fourier series with time variant coefficients as follows [12], [13]:

$$x(\tau) = \sum_{h=-\infty}^{\infty} X_h(t)\ e^{jh\omega\tau} \tag{1}$$

where, $\tau\epsilon[t, t+T)$, the coefficient $X_h(t)$ is a time-varying complex number and ω is equal to $2\pi/T$. Eq. (1) can be rewritten in the matrix form as follows:

$$x(\tau) = \boldsymbol{E}(\tau)\,\boldsymbol{X}(t) \tag{2}$$

here,

$$\boldsymbol{X}(t) = [\cdots\ X_{-2}(t)\ X_{-1}(t)\ X_0(t)\ X_1(t)\ X_2(t)\ \cdots]^T$$
$$\boldsymbol{E}(\tau) = [\cdots\ e^{-j2\omega\tau}\ e^{-j\omega\tau}\ 1\ e^{j\omega\tau}\ e^{j2\omega\tau}\ \cdots]$$

A. State-Space Equation

Considering the general expression of the state-space equation

$$\dot{x}(t) = a(t)\,x(t) + b(t)\,u(t) \tag{3}$$

where, $a(t)$ and $b(t)$ are periodic functions with period of T and the state variable $x(t)$ is in the form of (1). Then, the new state-space equation in the DHD is represented as follows [13]:

$$\dot{\boldsymbol{X}}(t) = (\boldsymbol{A} - \boldsymbol{D})\,\boldsymbol{X}(t) + \boldsymbol{BU} \tag{4}$$

where, $\boldsymbol{D}$ is the differentiation matrix and $\boldsymbol{A}$ and $\boldsymbol{B}$ are Toeplitz matrices formed by the harmonics of $a(t)$ and $b(t)$, respectively [13]. $\boldsymbol{U}$ is a vector formed by the harmonics of $u(t)$. Eq. (4) is the transformation of (3) into the DHD, where the state variable in (3) is $x(t)$ and in (4) are the harmonics of $x(t)$. The steady-state response of (4) is given by the following equation [13]:

$$\boldsymbol{X} = -(\boldsymbol{A} - \boldsymbol{D})^{-1}\boldsymbol{BU} \tag{5}$$

By comparing (3) and (4), it can be observed that the DHD transforms a linear time periodic (LTP) system to a linear time invariant (LTI) system. A particular case of (4) is the steady-state condition given by (5), which is reduced to a set of algebraic equations. Eq. (5) can be used to establish the steady-state condition of the state-space equation.

B. Phase-Shift of Periodic Signals

If a dynamic periodic signal $u(\tau)$ in the form of (1) is time shifted by t_0, i.e., $u(\tau - t_0)$, then we have [21]:

$$u(\tau - t_0) = \sum_{h=-\infty}^{\infty} U_h(t)\, e^{jh\omega(\tau - t_0)}$$
$$= \sum_{h=-\infty}^{\infty} U_h(t)\, e^{-jh\omega t_0}\ e^{jh\omega\tau} \tag{6}$$

This yields a new harmonic coefficient $U_h(t - t_0) = U_h(t)e^{-jh\omega t_0}$, which clearly shows that rotation of the coefficient $U_h(t)$ is the only effect of the frequency domain. This rotation is a linear function of the harmonic *h* which can be interpreted as addition of a linear phase to the original component. By assuming that ωt_0 is equal to α, (6) in the matrix form can be rewritten as follows:

$$u(\tau - t_0) = \boldsymbol{E}(\tau)\,\boldsymbol{SU}(t) \tag{7}$$

where, $\boldsymbol{S}$ is called the phase shift matrix which is a diagonal matrix of the following form [21]

$$\boldsymbol{S} = diag\left\{\ \cdots\ e^{j2\alpha}\ e^{j\alpha}\ 1\ e^{-j\alpha}\ e^{-j2\alpha}\ \cdots\right\}$$

According to (7), it can be observed that the harmonics vector of $u(\tau - t_0)$ is given by the following equation:

$$\boldsymbol{U}(t - t_0) = \boldsymbol{S}\,\boldsymbol{U}(t) \tag{8}$$

Equation (8) presents the harmonics of a phase-shifted function obtained from a non-phase-shifted function. Derivative of $\boldsymbol{U}(t - t_0)$ for dynamic analysis is given by the following equation [21]:

$$\dot{\boldsymbol{U}}(t - t_0) = \boldsymbol{S}\dot{\boldsymbol{U}}(t) \tag{9}$$

According to (9), it can be concluded that the harmonics of the derivative of $u(\tau - t_0)$ is equal to the harmonics of the derivative of $u(\tau)$ multiplied by a phase-shifting matrix. In [21], it is shown that by using properties given in (8) and (9), the dynamic harmonic response of the system to the input $u(\tau - t_0)$ can be directly obtained considering the dynamic harmonic response to input $u(\tau)$ by means of phase-shifting property, and there is no need to perform extra simulation.

III. Generalized Symmetrical Components Proposed by Tenti *et al.*

As explained in [24] and in contrast to classical symmetrical components, in generalized symmetrical components, zero sequence should be computed first and this sequence affects both positive and negative sequences. Required equations for calculating zero, positive and negative sequences are as follows.

$$f_0(t) = \frac{1}{3}\left(f_a(t) + f_b(t) + f_c(t)\right) \tag{1}$$

$$f_p(t) = \frac{1}{3}\left(f_a(t) - f_0(t) + f_b\left(t + \frac{T}{3}\right) - f_0\left(t + \frac{T}{3}\right) + f_c\left(t + \frac{2T}{3}\right) - f_0\left(t + \frac{2T}{3}\right)\right) \tag{2}$$

$$f_n(t) = \frac{1}{3}\left(f_a(t) - f_0(t) + f_b\left(t - \frac{T}{3}\right) - f_0\left(t - \frac{T}{3}\right) + f_c\left(t - \frac{2T}{3}\right) - f_0\left(t - \frac{2T}{3}\right)\right) \tag{10}$$

here, $f_a(t)$, $f_b(t)$ and $f_c(t)$ are the three phase signals in time domain. Based on (10), it can be seen that zero sequences in symmetrical components and its generalized representation are the same. Residual component which has a different value for each phase, $f_{ra}(t)$, $f_{rb}(t)$ and $f_{rc}(t)$ can be computed from the following equations [24].

$$\begin{aligned} f_a(t) &= f_p(t) + f_n(t) + f_0(t) + f_{ra}(t) \\ f_b(t) &= f_p\left(t - \frac{T}{3}\right) + f_n\left(t + \frac{T}{3}\right) + f_0(t) + f_{rb}(t) \\ f_c(t) &= f_p\left(t + \frac{T}{3}\right) + f_n\left(t - \frac{T}{3}\right) + f_0(t) + f_{rc}(t) \end{aligned} \tag{11}$$

Time domain operator in (10) and (11) can be converted to phase-shift matrix with α equal to $\pm 120°$ in frequency domain.

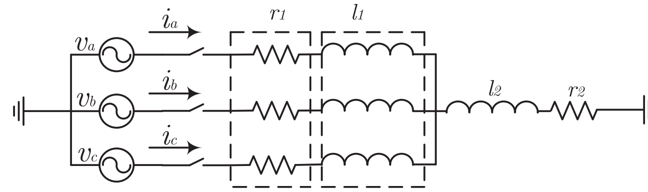

Fig. 1. Linear test system used in Section IV.

TABLE I
Harmonic Content of Input Three-Phase Voltages

Harmonic order	t < 0.15s			0.15s < t < 0.2s		
	"a"	"b"	"c"	"a"	"b"	"c"
1	1.2∢25°	0.9∢ − 100°	1∢90°	1.2∢25°	0.9∢ − 100°	1∢90°
3	0	0	0	1.8∢10°	0	0
5	0.6∢10°	0.36∢ − 140°	0.32∢ − 20°	0.6∢10°	0.36∢ − 140°	0.32∢ − 20°

According to (10), it is clear that both positive and negative sequences have no multiples of third harmonic $(3k, k = 1, 2\ldots)$ since by using phase-shift matrix with α equal to $\pm 120°$ in frequency domain, these harmonic components are not affected $(\pm 120° \times 3k,\ k = 1, 2\ldots)$ while in classical symmetrical components these sequences can contain multiples of third harmonic. Also, (10) shows that if multiples of third harmonic are not present in the waveforms, for other harmonic components, results of classical symmetrical components and its generalized representation are completely equal. In sinusoidal case, the residual component is absent and as shown in [4], this component in three-phase systems contain only multiples of third harmonic. Moreover, as concluded and shown by using numeric examples in [22] and [24], in a balanced three phase system, only positive and zero components are present in the waveforms. Moreover, in this case, generalized positive sequence component is made only by the first, 5th, 7th … harmonics; and in this case, generalized zero component is only made by multiples of third harmonic.

IV. Illustrative Example I: Non-Parallel Connection of Sequences Networks

In this section, by using a sample test system, it is shown that for a system in which only input sources are unbalanced, if multiples of third harmonic are added to the phase *"a"*, classical symmetrical components and direct time domain solution will lead to the same results for response of phase *"a"*; however, obtained results by classical symmetrical components and direct time domain solution for phases *"b"* and *"c"* are not the same. Linear system shown in Fig. 1 is used. The parameters of the linear system depicted in Fig. 1 are as follows:

Positive sequence: $r_p = r_1 = 0.1\ \Omega$ and $l_p = l_1 = 2$ mH.
Negative sequence: $r_n = r_1 = 0.1\ \Omega$ and $l_n = l_1 = 2$ mH.
Zero sequence: $r_0 = r_1 + 3r_2 = 7.1\ \Omega$ and $l_0 = l_1 + 3l_2 = 17$ mH.

Input voltages are given in Table I for different intervals. It should be noted that for the sake of simplicity, all initial

TABLE II
HARMONIC CONTENT OF DIFFERENT SEQUENCES OF INPUT THREE-PHASE VOLTAGES

Harmonic order	t < 0.15s			0.15s < t < 0.2s		
	P	N	Z	P	N	Z
1	0.94∢ 6.42°	0.25∢ 128.6°	0.37∢ 33.69°	0.94∢ 6.42°	0.25∢ 128.62°	0.37∢ 33.69°
3	0	0	0	0.6∢ 10°	0.6∢ 10°	0.6∢ 10°
5	0.3∢ 58.58'	0.24∢ − 18.18°	0.22∢ − 21.02°	0.3∢ 58.58°	0.24∢ − 18.18°	0.22∢ − 21.02°

conditions are set to zero. It is worth noting that this test system is also implemented in Electromagnetic Transient Program (EMTP) software as a reference with time step of 10 μs in order to perform conventional lumped circuit simulation and validate time domain waveforms resulted from DHD method by analyzing sequence networks. DHD approach uses numerical integration method with the same time step as EMTP.

Considering the reported values in Table I for input three-phase voltages and using classical symmetrical components [23], Table II shows the different sequences calculated by classical symmetrical components for different time intervals for each harmonic component. Table II will be used in the following subsections and Section V. It should be noted that in this test system (and also test systems of Section V and Section VII), for the sake of simplicity, low frequency harmonics are considered. However, without limit, analyzing can be extended to higher order harmonics as shown and analyzed in Section VIII.

A. $t < 0.15$ s – Without Third Harmonic

According to the calculated values listed in Table II, during this time interval, there are no multiples of third harmonic present in the positive, negative and zero components. DHD methodology is used in order to perform dynamic harmonic analysis in frequency domain based on the sequence networks of the system under study. Three-phase source currents are depicted in Fig. 1 for the considered time interval. Considering this figure, it is clear that during this time interval, calculated results by performing classical symmetrical components and those obtained by direct time domain solution using EMTP are in good agreement (see Fig. 2).

B. 0.15 s $< t < 0.2$ s – With Third Harmonic

Considering Table II, it is concluded that during this time interval, third harmonic component is added to positive, negative and zero sequences with the same value. Three-phase source currents are shown in Fig. 3. According to this figure, it can be seen that during this time interval, obtained results by performing classical symmetrical components and direct solution using EMTP will lead to the same results for response of phase *"a"*. However, calculated results by classical symmetrical components and direct time domain solution for phases *"b"* and *"c"* are not the same.

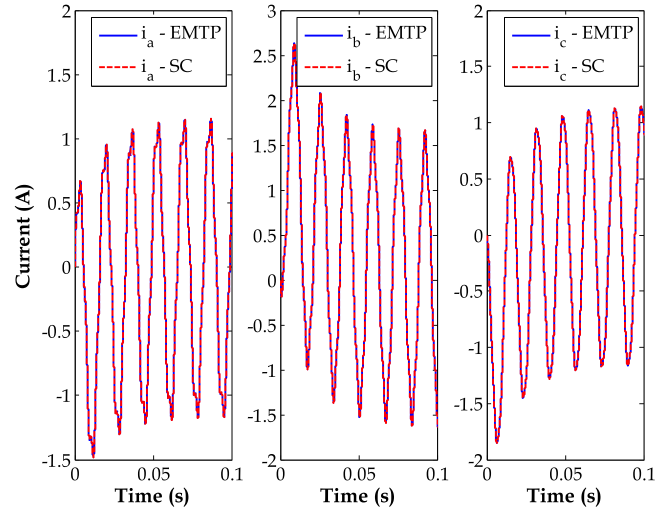

Fig. 2. Source currents calculated by EMTP and symmetrical components (SC) for $t < 0.15$ s.

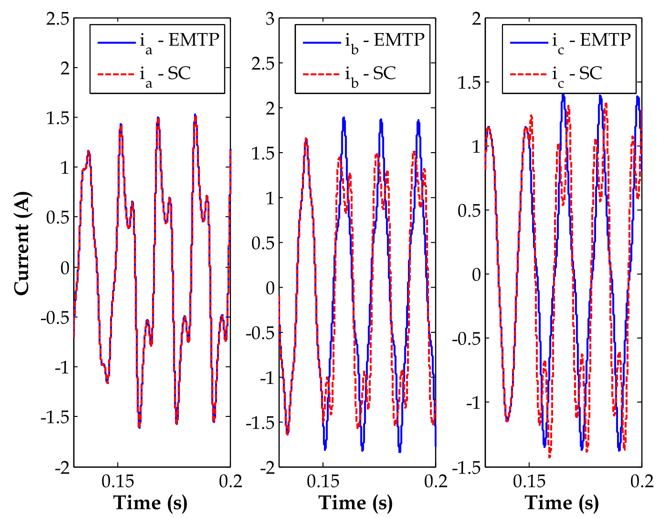

Fig. 3. Source currents calculated by EMTP and symmetrical components (SC) for 0.15 s $<$ t $<$ 0.2 s.

C. Equivalent Circuit for Triplen Harmonics

As mentioned before and shown by a numeric example in Section IV. A, classical symmetrical components provides exact solution for three phases if multiples of third harmonic are not present in the inputs. Moreover, in Section IV. B, it was shown that if multiples of third harmonic are only present in phase *"a"*, provided results by classical components leads to the exact results for phase *"a"* while results of phases *"b"* and *"c"* are not correct. Therefore, in this part of the paper, only equivalent circuit for multiples of third harmonic are analyzed. It is assumed that triplen harmonics are only present in one phase and it will be shown that this assumption is essential and superposition feature can be used if other phases contain multiples of third harmonic. Fig. 4 shows the equivalent circuit of Fig. 1 for multiples of third harmonic in frequency domain. This figure clearly shows that current of phase *"b"* and current of phase *"c"* are identical and also different from current of phase *"a"*. In this system, phase

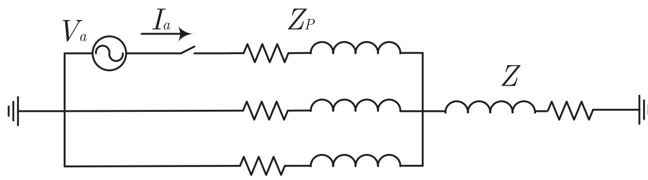

Fig. 4. Equivalent circuit for multiples of third harmonic in phase *"a"*.

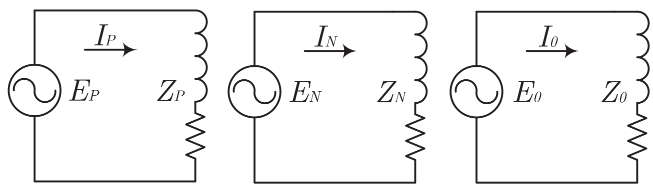

Fig. 5. Equivalent circuit for different sequences.

"a" current is calculated as follows:

$$I_a = \frac{V_a}{Z_{eq_1}} \tag{12}$$

Z_{eq_1} is calculated as follows:

$$Z_{eq_1} = \frac{\frac{Z_P}{2} \times Z}{\frac{Z_P}{2} + Z} + Z_P = Z_P \left(\frac{Z_P + 3Z}{Z_P + 2Z} \right) \tag{13}$$

According to classical symmetrical components and since it is assumed that multiples of third harmonic are only present in phase *"a"*, it is concluded that $E_P = E_N = E_0$ which are equal to $\frac{1}{3}V_a$. Considering Fig. 5 which depicts equivalent circuits for different components, phase *"a"* current is equal to $I_P + I_N + I_0$.

$$I_a = \frac{V_a}{3} \left(\frac{1}{Z_P} + \frac{1}{Z_N} + \frac{1}{Z_0} \right) = \frac{V_a}{3} \left(\frac{2}{Z_P} + \frac{1}{Z_P + 3Z} \right) = \frac{V_a}{Z_{eq_2}} \tag{14}$$

Z_{eq_2} is calculated as follows:

$$Z_{eq_2} = \frac{1}{\frac{1}{3}\left(\frac{3Z_P + 6Z}{Z_P(Z_P + 3Z)} \right)} = Z_P \left(\frac{Z_P + 3Z}{Z_P + 2Z} \right) \tag{15}$$

Comparing (13) and (15), it is clear that Z_{eq_1} and Z_{eq_2} are equal. Therefore, for a third harmonic in phase *"a"*, using classical symmetrical components provides the exact response of phase *"a"*. However, based on classical symmetrical components according to which positive and negative sequences are shifted for $\pm 120°$ for other phases, phases *"b"* and *"c"* have the same third harmonic current as phase *"a"*. Considering Fig. 4, this result is not correct. In order to overcome this drawback of classical symmetrical components, concept of generalized symmetrical components is used. Since using classical symmetrical components leads to the exact answer for phase *"a"* response, it is concluded that:

$$I_P^{GSC} + I_N^{GSC} + I_0^{GSC} + I_{ra}^{GSC} = I_P^{SC} + I_N^{SC} + I_0^{SC} \tag{16}$$

Noting that $I_0^{GSC} = I_0^{SC}$ for all harmonic components and $I_{r_a}^{GSC}$ is made only by multiples of third harmonic. Also, I_P^{GSC} and I_N^{GSC} have no multiples of third harmonic. Equation (16) for triplen harmonics can be rewritten as follows:

$$I_{r_{a\,h}}^{GSC} = I_{P_h}^{SC} + I_{N_h}^{SC} \text{ for } h = 3k,\ k = 1, 2, 3 \ldots \tag{17}$$

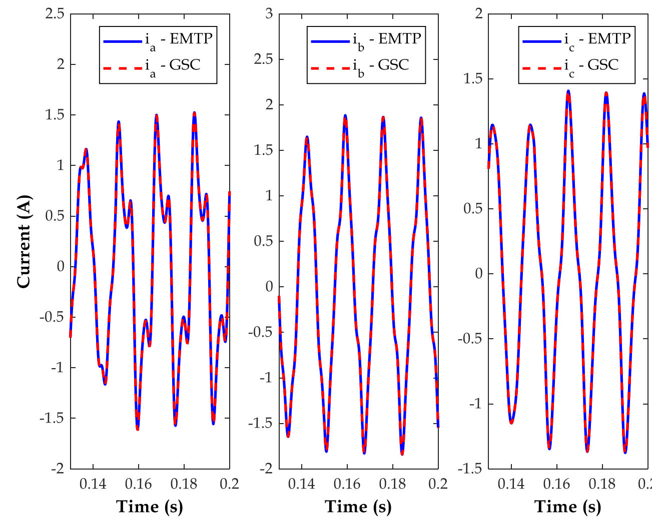

Fig. 6. Source currents calculated by EMTP and generalized symmetrical Components (GSC) for 0.15 s $< t <$ 0.2 s.

According to (17), it is concluded that residual component of phase *"a"* is formed by multiples of third harmonic present in the summation of positive and negative sequences. According to Fig. 4, current responses in phases *"b"* and *"c"* are identical; hence, it is concluded that $I_{r_b}^{GSC} = I_{r_c}^{GSC}$. Considering $I_{r_a}^{GSC} + I_{r_b}^{GSC} + I_{r_c}^{GSC} = 0$, it is clear that $I_{r_b}^{GSC} = I_{r_c}^{GSC} = -0.5 I_{r_a}^{GSC}$.

If the concept of generalized symmetrical components is used in order to modify the output results of classical symmetrical components, three-phase source currents for 0.15 s $< t <$ 0.2 s will be as depicted in Fig. 6. According to this figure, it is clear that by using generalized symmetrical components and considering equivalent circuit for triplen harmonics which is required to find the relation between residual components, exact responses for phases *"b"* and *"c"* are obtained. Harmonic content of three- phase source currents are depicted in Fig. 7 which shows that using classical symmetrical components and its generalized representation lead to different results for third harmonic in phases *"b"* and *"c"*. It is important to mention that using equivalent circuit for multiples of third harmonic in order to find the relation between residual components is vital. As it will be demonstrated in the next section, if system configuration is unbalance, for instance during unbalanced faults, based on the connection of the sequence networks, it may be necessary to directly calculate multiples of third harmonic by using their equivalent circuit and then modify the results of classical symmetrical components.

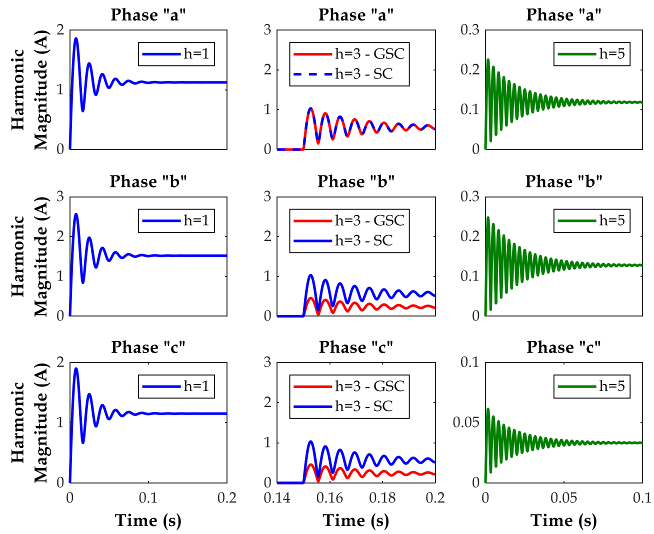

Fig. 7. Harmonic content of three-phase source currents.

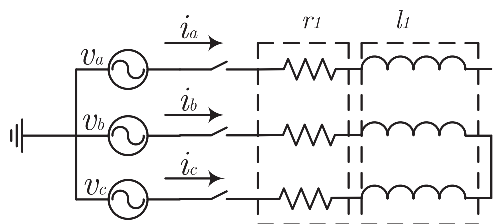

Fig. 8. Linear test system used in Section V.

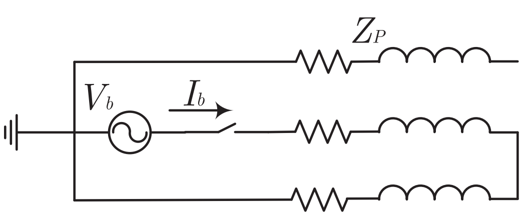

Fig. 9. Equivalent circuit for multiples of third harmonic.

V. Illustrative Example II: Parallel Connection of Sequences Networks

In this section of the paper, the shown test system in Fig. 8 is considered which depicts the circuit diagram for a phase-phase fault. For the sake of simplicity, the used numerical values in this section for impedances are the same as ones used in previous section. Also, in this case, third harmonic source is only present in phase *"b"* and it has the same value as the phase *"a"* in the previous section. Figs. 9 and 10 depict frequency domain representation of equivalent circuit for multiples of third harmonic in phase *"b"* and connection of sequence networks for phase-phase fault, respectively. Moreover, based on Fig. 10 and considering Table II which shows $E_P = E_N = \frac{1}{3}V_b$, it is clear that for third harmonic $I_P = I_N = 0$. Hence, residual components for three phases cannot be obtained by analyzing the sequence networks using classical symmetrical components. Therefore,

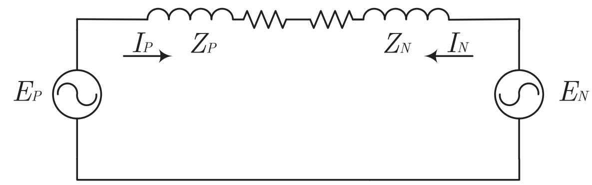

Fig. 10. Connection of sequence networks for a phase-phase fault.

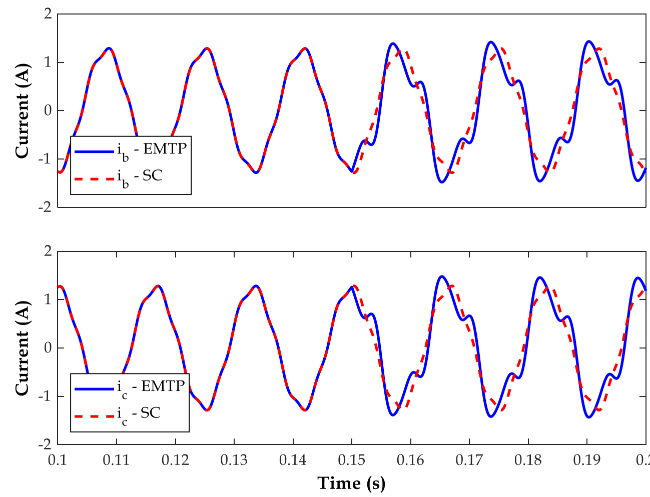

Fig. 11. Current of phases *"b"* and *"c"* calculated by EMTP and symmetrical components (SC).

for obtaining residual components, equivalent circuit for triplen harmonics should be directly used. In this system, by using the concept of generalized symmetrical components it can be seen that $I_0^{GSC} = 0$; then, it is concluded $I_{r_a}^{GSC} = 0$ which also shows $I_{r_b}^{GSC} = -I_{r_c}^{GSC}$. Moreover, according to Fig. 9, third harmonic current in phase *"b"* (I_b) is equal to $\frac{V_b}{2Z_P}$ and $I_b = -I_c$. Since zero sequence current is equal to zero, then residual component of phase *"b"* current is calculated by $\frac{V_b}{2Z_P}$. Fig. 11 depicts current of phases *"b"* and *"c"* obtained by using EMTP and classical symmetrical components. This figure also shows that calculated results by performing classical symmetrical components and those obtained by direct time domain solution using EMTP are in good agreement for $t < 0.15$ s; however, for $t > 0.15$ s results are not the same. By considering equivalent circuit for multiples of third harmonic and using the concept of generalized symmetrical components, results of classical symmetrical component can be modified as shown in Fig. 12. According to this figure, it is clear that for $t > 0.15$ s using generalized symmetrical components leads to exact responses for phases *"b"* and *"c"*. Fig. 13 depicts harmonic content of current of phases *"b"* and *"c"*. It can be seen that by using classical symmetrical component it is not possible to analyze the system for a line-line fault in the presence of third harmonic since positive and negative voltages have the same value which leads to $I_P = I_N = 0$ for multiples of third harmonic. However, by considering equivalent circuit for multiples of third harmonic and generalized symmetrical components, results of classical components can be corrected.

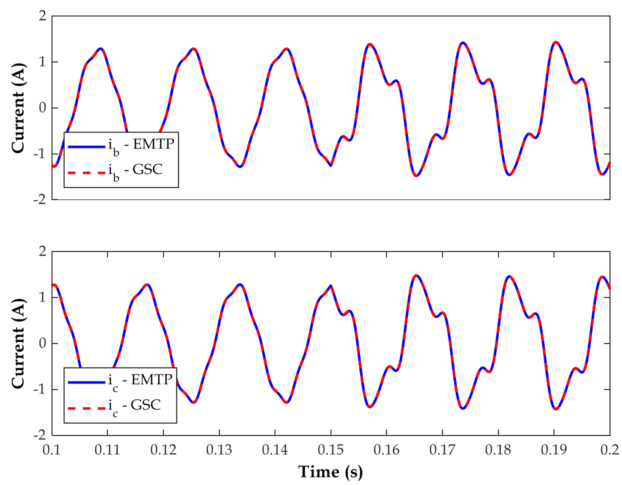

Fig. 12. Current of phases *"b"* and *"c"* calculated by EMTP and generalized symmetrical components (GSC).

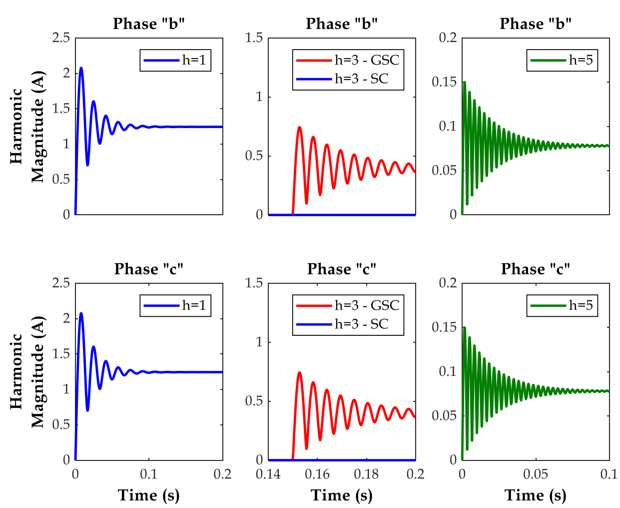

Fig. 13. Harmonic content of current of phases *"b"* and *"c"*.

VI. Analyzing Unbalanced Systems in Presence of Harmonic Distortion

In previous sections, by using simple test systems, limits of classical symmetrical components for analyzing three-phase unbalanced systems in the presence of multiples of third harmonic have been investigated. As explained and shown by numeric examples, if triplen harmonics are not present in the system, performing classical symmetrical components leads to the exact values under both transient and steady state conditions. Moreover, application of generalized symmetrical components in analyzing three-phase unbalanced system has been studied. However, considering both illustrative examples, it is concluded that the equivalent circuit for multiples of third harmonic should be analyzed in order to calculate residual components in three phases and modify the output results of classical symmetrical components to reach the exact responses. The following steps are required for analyzing three-phase systems by using generalized symmetrical components in frequency domain: Step 1- Sequence networks and equivalent circuit for multiples of third harmonic are analyzed by performing DHD; and then, different sequences (positive, negative, zero and residuals) are obtained. Step 2- Basic equations of generalized symmetrical components are used in order to calculate three-phase currents or voltages in frequency domain. Step 3- Equation (1) is applied to the calculated values in Step 2 in order to obtain time domain responses of three-phase currents or voltages. Flowchart of the proposed algorithm of this paper for dynamic analyzing of unbalanced three-phase systems in the presence of harmonic distortion is shown in Fig. 14. It should be noted that this flowchart is only used for triplen harmonics since classical symmetrical components and generalized symmetrical components lead to the same results for other harmonic components. It is important to calculate residual sequences of three-phases in order to modify the results of classical symmetrical components. In order to generalize the proposed method of this paper, sequence networks and equivalent circuit for multiples of third harmonic can be analyzed individually and residual components are calculated as follows:

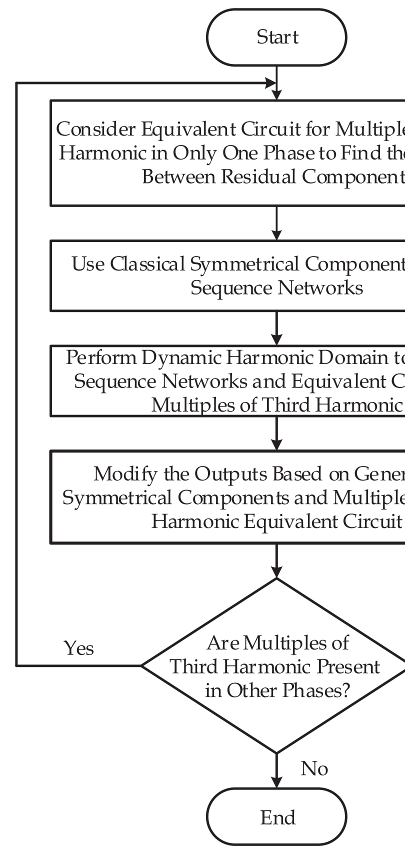

Fig. 14. Flowchart of analyzing unbalanced three-phase systems in the presence of harmonic distortion.

$$f_{r_{i_h}}^{GSC} = f_{i_h}^{eq} - f_{0_h}^{SC} \quad (18)$$

here, f can be either current or voltage, $h = 3k$ for $k = 1, 2, 3 \ldots$ and $i = a,\ b,\ c$. Moreover, f^{eq} is calculated by analyzing equivalent circuit for multiples of third harmonic. According to (18), it is also concluded that f^{eq} can be directly used to

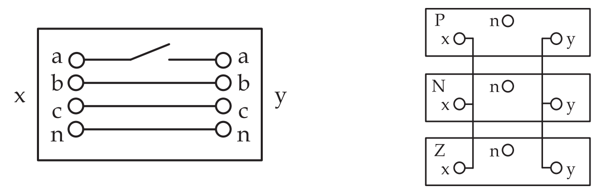

Fig. 15. Sequence interconnections for phase *"a"* open fault.

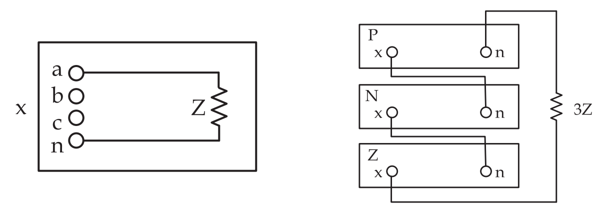

Fig. 16. Sequence interconnections for phase *"a"* to ground fault.

modify the results of classical symmetrical components if it is not necessary to obtain different sequences individually.

It is worth noting that in some cases, residual components of three phases can be obtained without solving equivalent circuit for multiples of third harmonics directly and this circuit is only required to find the relations between residual components (see Section VI). However, in some cases direct analyzing of equivalent circuit for multiples of third harmonic is vital so that if this circuit is not analyzed it is not possible to modify the results of classical symmetrical components (see Section V).

Considering classical symmetrical components, if multiples of third harmonic are present in the system, it can be seen that $E_P = E_N = E_0 = \frac{1}{3}V_i$ in which $i = a,\ b,\ c$. Considering triplen harmonics, since positive, negative and zero component voltages are equal, it can be concluded that for an unbalanced condition in which sequences are connected in parallel for instance phase- phase fault for shunt unbalance (See Section V) or one phase open for series unbalance (See Fig. 15), three sequence currents are equal to zero. Therefore, in such cases, residual components of three phases cannot be directly determined using results of symmetrical components and equivalent circuit for multiples of third harmonic should be analyzed. It is worth noting that if sequences are connected in parallel and no current flows to ground (phase-phase fault), $I_{0_h} = 0$ and equivalent circuit for triplen harmonic directly gives residual components of three phases. However, if sequences are connected in parallel and current can flow to ground (phase-phase-ground fault), $I_{0_h} \neq 0$ and equivalent circuit for triplen harmonics gives residual component along with zero sequence. In fact, in this systems, current of each part is equal to $I^{GSC}_{r_{i_h}} + I_{0_h}$ in which $i = a,\ b,\ c$. It should be noted that for single line to ground fault which is the most common fault in power systems, it is possible to modify the results of classical symmetrical components directly without analyzing equivalent circuit for multiples of Third harmonic since in such case, sequences are not connected in parallel as depicted in Fig. 16. In this case, at the fault location, $I_b = I_c = 0$ for all harmonic components. Considering triplen harmonics, it is concluded that $I^{GSC}_{r_{a\,h}} = I^{SC}_{P_h} + I^{SC}_{N_h}$ and $I^{GSC}_{r_{b_h}} + I_{0_h} = I^{GSC}_{r_{c_h}} + I_{0_h} = 0$ and therefore, $I^{GSC}_{r_{b_h}} = I^{GSC}_{r_{c_h}} = -I_{0_h}$.

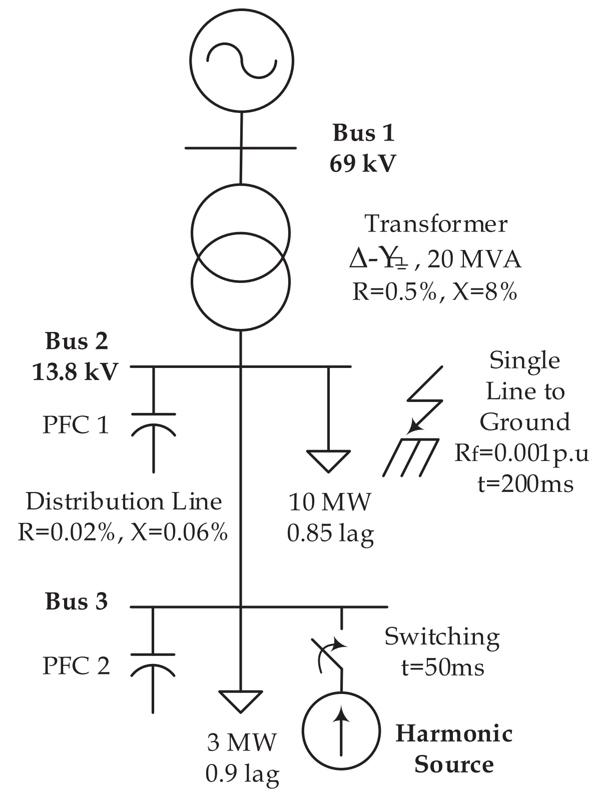

Fig. 17. Single line diagram of the test system used for Section VII.

VII. Three Bus System With Harmonic Source

In order to clarify and magnify the advantages and accuracy of the proposed approach in this paper for dynamic harmonic analysis using generalized symmetrical components, consider the three bus industrial system of Fig. 17. According to this figure, the system is supplied by the utility through a 69 kV- Delta/13.8 kV-Grounded Star transformer and the local plant distribution system operates at 13.8 kV. Moreover, as it can be seen in this figure, Buses 2 and 3 are equipped with Power Factor Correctors (PFCs) and as is typically done, leakage and series resistance of the banks are neglected in this study. In this test system, it is assumed that each PFC fully compensates for the bus load; therefore, the capacitor fundamental susceptance can be found from the load flow data. Considering that the "Harmonic Source" is not connected to Bus 3, load flow results for fundamental frequency are listed in Table III in p.u. noting that 10 MVA and 13.8 kV are used as the base values for power and voltage, respectively. In order to perform harmonic analysis, by using load flow results reported in Table III, PFCs and loads connected to Bus 2 and Bus 3 are modeled as constant impedances (C for each PFC and series RL circuit for each load) obtained from the given kVA at 60 Hz [25]. Also, frequency scan analysis can be helpful to verify if resonance conditions exist in the system. Determining the seen impedances from Bus 2 and Bus 3, it

TABLE III
LOAD FLOW RESULTS (IN P.U.)

Bus #	P_G	Q_G	P_{Load}	Q_{Load}	$Q_{Injected}$	V
1	1.304	0.069	0.000	0.000	0.000	$1.000\angle 0.000°$
2	0.000	0.000	1.000	0.620	0.620	$0.995\angle$-2.995°
3	0.000	0.000	0.300	0.145	0.145	$0.995\angle$-3.050°

TABLE IV
HARMONIC CONTENT OF "HARMONIC SOURCE" CURRENT IN FIG. 17

Phase	Harmonic Order		
	1	3	7
"a"	$0.20 \times V_{1_{Bus\,3-a}}$	$0.15 \times V_{1_{Bus\,3-a}}$	0.00
"b"	0.00	0.00	$0.05 \times V_{1_{Bus\,3-b}}$
"c"	$0.25 \times V_{1_{Bus\,3-c}}$	$0.10 \times V_{1_{Bus\,3-c}}$	0.00

can be concluded that the system forms two resonance frequencies, one around the 6th harmonic and the other one around the 51th harmonic.

A. Switching of "Harmonic Source"

In this test system, steady-state initialization is performed by using (5) which leads to results of load flow for the voltages of buses 1, 2 and 3 (see Table III). "Harmonic Source" connects to Bus 3 through an ideal switch at $t = 50$ ms. Table IV shows its associated harmonic content for each phase. As it can be seen in this table, in all three phases, harmonic components depend on fundamental component of Bus 3 voltage. Moreover, harmonic content of each phase is different from other phases which makes this harmonic source completely unbalanced. In this case, considering the concept of generalized symmetrical components, since the system configuration is balanced, the same procedure as explained for Illustrative Example I (see Section IV) can be followed. It should be noted that third harmonic is present in both *"a"* and *"c"* phases; therefore, residual components can be directly obtained considering the fact that sequence components for third harmonic of each phase should be analyzed individually. Fig. 18 depicts three phase currents of transformer secondary side determined by the concept of generalized symmetrical components during the switching of "Harmonic Source". It is worth noting that during steady state condition, Total Harmonic Distortion (THD) for *"a"*, *"b"* and *"c"* currents are 12.080%, 9.415% and 7.876%, respectively. Also, THD of Bus 2 phase voltages *"a"*, *"b"* and *"c"* (with respect to ground) is 2.210%, 3.513% and 1.475%, respectively. It should be noted that three phase currents of transformer primary side contain third harmonic which is due to residual component since zero sequence current at primary side is equal to zero because of delta connection of this side. Considering phase *"a"* current of transformer secondary side, it is worth noting that 1th, 3th and 7th harmonics of zero sequence are 52.30%, 36.68% and 28.38% of residual component, respectively which emphasized on that the transformer connection can have significant impacts on harmonic propagation.

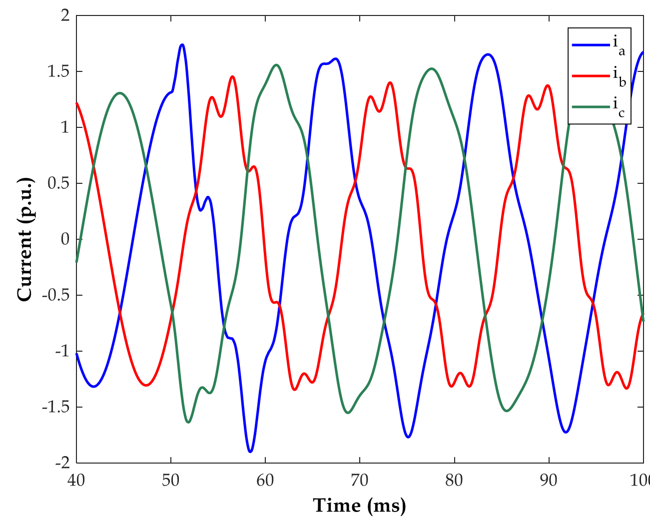

Fig. 18. Three phase currents of transformer secondary side during the switching of "Harmonic Source".

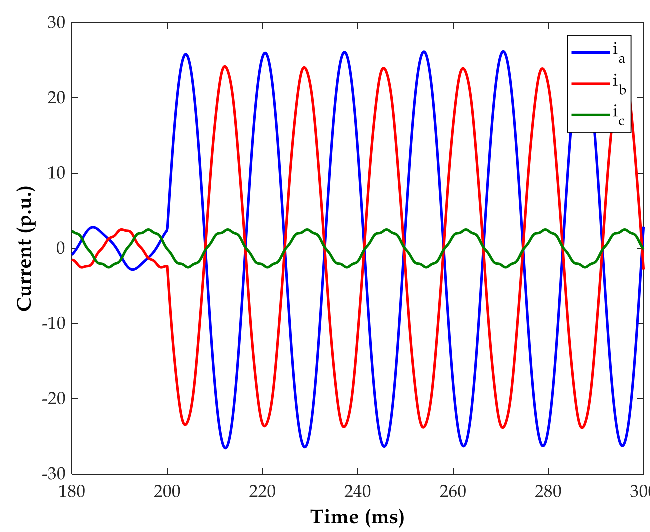

Fig. 19. Three phase currents of transformer primary side during single line to ground fault.

B. Single Line to Ground Fault at Bus 2

It is assumed that a single line to ground fault occurs on Bus 2 through a fault impedance of 0.001 p.u. at t = 200 ms. In this case, at the fault location, sequences are connected as shown in Fig. 13 and it is possible to modify the results of classical symmetrical components directly without analyzing equivalent circuit for triplen harmonics. Fig. 19 illustrates three phase currents of transformer primary side obtained by using the concept of generalized symmetrical components. In this case, as it can be seen in this figure, since phase *"a"* voltage at Bus 3 reaches a very low value due to short circuit fault, harmonic content of "Harmonic Source" at phase *"a"* reduces significantly.

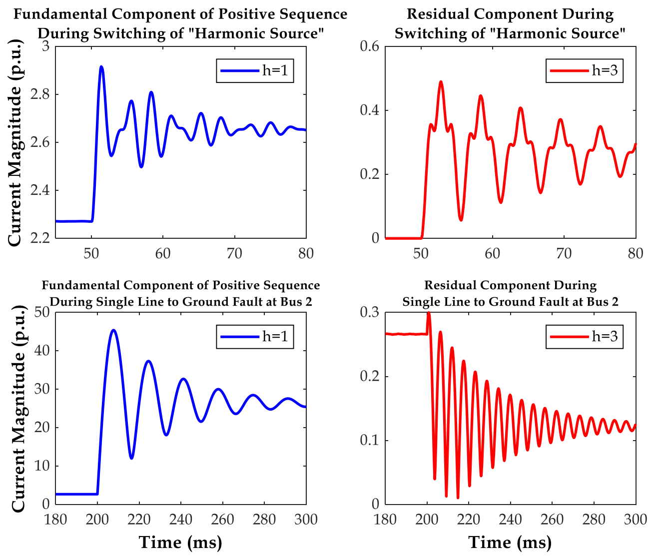

Fig. 20. Fundamental and residual components of phase *"a"* current of transformer primary side during single line to ground fault.

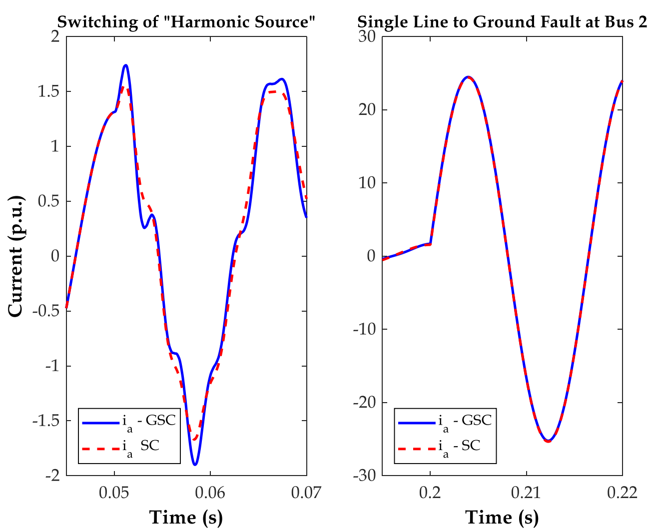

Fig. 21. Phase *"a"* current of transformer primary side during "Harmonic Source" switching and single line to ground fault.

Fig. 20 shows fundamental component of positive sequence and residual component of phase *"a"* current at the transformer primary side during switching of "Harmonic Source" and single line to ground fault at Bus 2. As expected, during single line to ground fault, magnitude of fundamental component of positive sequence (denoted as $h = 1$ in Fig. 20) increases significantly so that maximum value of its magnitude is 45.39 p.u. at $t = 207.6$ ms. However, as mentioned before, during fault interval, magnitude of residual component (denoted as $h = 3$ in Fig. 20) reduces due to severe voltage drop at phase *"a"* of buses 2 and 3. Considering phase *"a"* current of transformer secondary side during "Harmonic Source" switching and single line to ground fault at Bus 2, comparison between generalized symmetrical component and classical symmetrical component is performed in Fig. 21. According to this figure, it can be seen that during

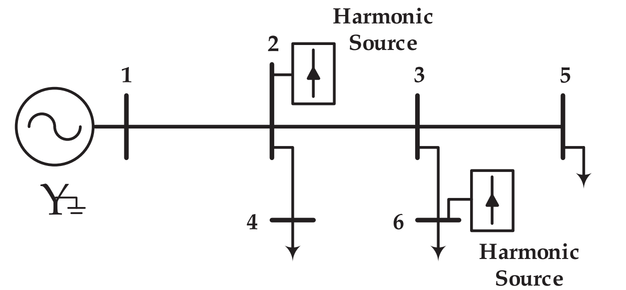

Fig. 22. Single line diagram of the lumped-parameters network used for Section VIII, taken from [20].

single line to ground fault in which injected third harmonic due to "Harmonic Source" is low, results of generalized symmetrical components and classical symmetrical components are in good agreement. However, results can have significant differences if level of third harmonic injection is considerable in comparison with other harmonic components.

VIII. Six Bus System With Two Harmonic Sources

The six bus test system presented in [20] is adopted for this case study in order to provide the detailed process of numerical solution. Single line diagram of the used test system is depicted in Fig. 22. The used numerical values are the same as ones used in [20]. However, it should be noted that zero sequence parameters for each transmission line are assumed to be equal to positive sequence parameters. Also, each phase of the connected source to bus 1 is modeled by employing a voltage source in series connection with an impedance and voltages in phases *"b"* and *"c"* are considered to be pure sinusoidal waveforms. Moreover, all loads have unity power factor. In this test case, two single phase electronic devices which inject 3th, 5th, 7th, 9th and 11th harmonics into the grid are connected to phase *"a"* of bus 2 and bus 6. The computer used for the presented simulations is Intel 2.10 GHz Central Processing Unit (CPU) with 8 GB of Random Access Memory (RAM). For transient analysis and considering time in electrical angle, the used time step for the numerical integration in order to determine transient response is equal to 0.02 rad.

A. *Steady State Response*

Three-phase steady state harmonic analysis is an important subject in analyzing modern power systems especially in unbalanced power systems including power electronic devices. As shown by Illustrative Example I, if system configuration is balanced and harmonic sources are modeled by using current (or voltage) sources, results of symmetrical components can be directly used and output results can be modified based on the concept of generalized symmetrical components. This important feature can be used to improve results of harmonic power flow in which it is usually assumed that system structure is balanced.

Considering eleven harmonics according to the highest present harmonic order in the system, steady state response can be efficiently achieved for each sequence network by using (5). However, results should be modified according to concept

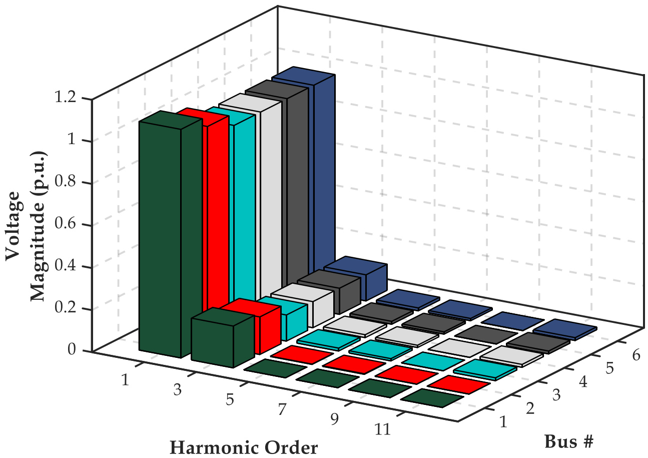

Fig. 23. Harmonic content of steady state voltages.

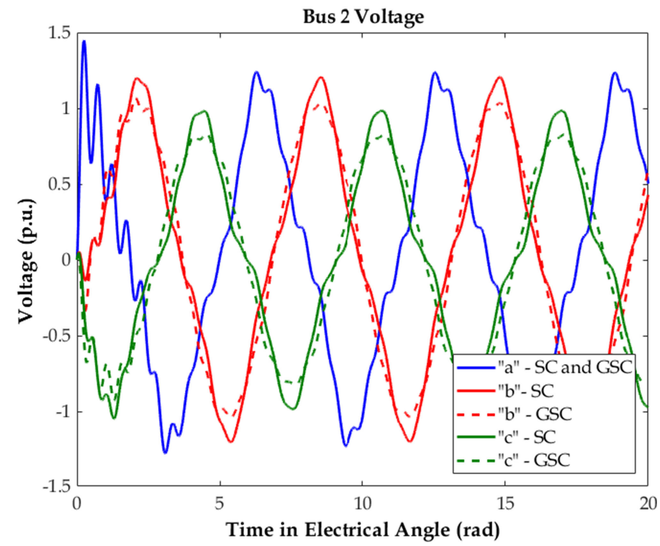

Fig. 24. Three phase voltages of bus 2 calculated by both symmetrical components (SC) and generalized symmetrical components (GSC).

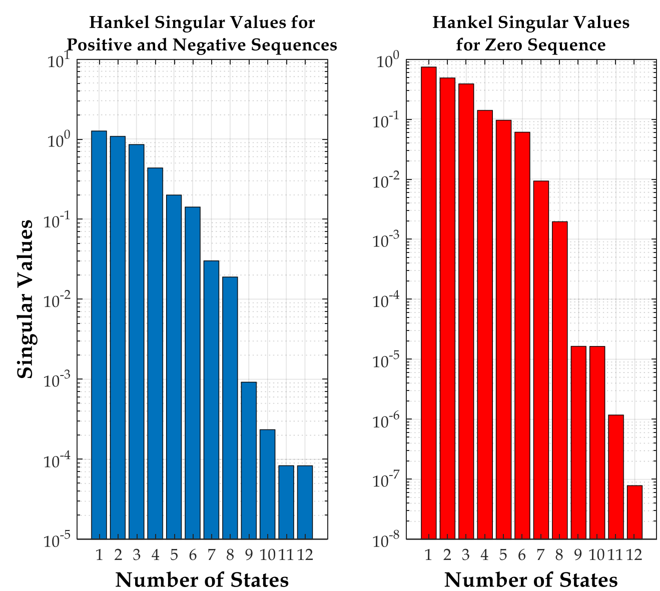

Fig. 25. Hankel singular values corresponding to different sequences of the test system shown in Fig. 22.

of generalized symmetrical components (see Section V). In this case, the total required time is equal to 0.012 s. Fig. 23 depicts harmonic content of phase *"a"* voltage for different buses. According to this figure, it is concluded that due to high value of third harmonic in all buses, large difference between results of symmetrical components and generalized symmetrical components is expected. For instance, by using symmetrical components, THD value for voltage of phase *"b"* at bus 2 is equal to 14.77% while using generalized symmetrical components this value is equal to zero which is clear from the system configuration.

B. Transient Response

In this case, all initial conditions are assumed to be zero and all three sources are simultaneously applied at $t = 0$ s. Using DHD, total required CPU time for analyzing sequence networks and then modifying the results according to generalized symmetrical components is equal to 4.167 s. Results of both symmetrical components and generalized symmetrical components for bus 2 three phase voltages are depicted in Fig. 24. According to this figure and considering transient response, maximum difference between results of symmetrical components and generalized symmetrical components for voltage of phase *"b"* is equal to 0.206 p.u. while this value is equal to 0.201 p.u. for steady state condition. As discussed in previous sections and as shown in Fig. 24 for this case study, depending on the level of triplen harmonics in the system in comparison with other harmonic components, results of symmetrical components and generalized symmetrical components can have significant differences.

It is worth noting that considering full order DHD system, dimension of each sequence network is equal to $12 \times (2 \times 11 + 1) = 276$ states. As discussed in [26], very large systems and switched networks require a large amount of computational resources if modeled in the DHD. However, as proposed in [27], balanced realization can be used in order to obtain reduced-order model for the electrical network which preserves the majority of the system characteristics. Hankel singular values that define the energy of each state in the system based on controllability and observability gramians are depicted in Fig. 25 for different sequences. Based on the magnitudes of these singular values and by defining a dominancy condition, order of each sequence can be reduced. For different sequence networks, considering Fig. 25, maximum and minimum values for Hankel singular values are equal to 1.257 and 8.316×10^{-5}, respectively. By defining dominancy condition of 10^{-3}, an order of 8 is chosen for reduced order models of positive, negative and zero sequences. Therefore, dimension of each sequence network is reduced to $8 \times (2 \times 11 + 1) = 184$ states. In this case, using reduced order model, total required CPU time for analyzing sequence networks and then modifying the results according to generalized symmetrical components reduces to 3.021 s.

IX. Conclusion

In this paper, using DHD approach, it was shown that classical symmetrical components proposed by Fortescue is not applicable in the presence of triplen harmonics in sequence domain. Also, it was shown that under this condition, generalized symmetrical components proposed by Tenti *et al*. can be employed in order to determine different sequences by using phase domain values. However, it introduces a new sequence component which has a different value for each phase and cannot be directly obtained based on sequence networks. In this paper, it was shown that for analyzing unbalanced three phase systems under harmonic distortion in sequence domain, it is essential to investigate equivalent circuit for triplen harmonics in order to calculate a part of zero sequence (which has triplen harmonics) and residual sequence. However, as discussed and shown by numeric examples, if sequence networks are not connected in parallel, it is possible to use classical symmetrical components and modify the output results to compute different sequences according to the concept of generalized symmetrical components including residual component.

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