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Development of a Novel Harmonics Estimation Approach

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Abstract: In this paper, a new fuzzy ADALINE neural network based method is presented to estimate the harmonics symmetric components exist in three-phase distribution network signals. The amplitude and phase components of the fundamental harmonic and the harmonics of each phase are extracted initially via a fuzzy ADALINE neural network. The positive, negative, and the zero sequences are then obtained from the harmonics considered in this system applying an independent Fortescue Transform for each harmonic. The proposed estimator is simulated in MATLAB/Simulink in order to assess the functionality of the method. The simulation results show higher efficiency of the proposed method in symmetric components estimation of an artificial three-phase signal harmonics and its higher performance in extracting such components in compare with that of the processing unit structure in a sample three-phase system under unbalance and nonlinear loads existence. The proposed system can be applied in power quality monitoring and be used as a control strategy in custom power devices, according to its advantageous such as fast respond, high accuracy, and low calculation extent.

Key words: Fuzzy ADALINE Neural Network, Fortescue Transform, Harmonics Symmetric Components, Fuzzy Regulator, Power Quality.

INTRODUCTION

Recent increase in utilization of asymmetric and unbalance loads such as inductive furnaces, inverter drives of electric machines speed control, and the power electronic converters, has created major risks for the power distribution systems. The recognition of nonlinear loads cause harmonics and determination of voltage and current unbalance rate, highly matter in fields such as power quality monitoring (IEEE Standard, 1995; IEEE Standard, 1992), power quality conditioning in distribution systems by creating a reference signal for the power electronics based quality conditioning devices (custom power devices) (Acha, 2002; Mostafa, 2004; Hingorani, 1995), digital protection, and harmonic restraint relays (SIPROTEC Numerical Protection Relays, 2002). This has led to the presentation of new symmetric components and harmonics amplitude and phase measuring and analysis. Among the presented methods, the algorithms with low calculation size and high convergence speed in real-time utilizations are applicable. Several methods have been reported for estimation of amplitude and phase angle of voltage and current harmonics possessing signals. One of these methods is based on the instant reactive power and is restricted to the ideal feeding voltage waveform operational condition, which leads to its weak operation under practical conditions where the voltage waveforms are distorted (Montanari, 1994). As an alternate for the mentioned method, the Park transform and the notch filters approaches are presented, which face with disadvantageous such as low accuracy and sensitivity to the frequency and distribution system parameters variations (Holng-Seok, 1999). The fast Fourier transform and its faster version, discrete Fourier transform are applied then in order to overcome the problems of the previous algorithms. Although the mentioned approaches can operate under non-sinusoidal voltage waveform existence condition, their dependency on the width of the selected window and their error under load dynamic variation condition are disadvantageous one can name for them (Brigham, 1988). The Kalman filter is introduced as a recursive estimator. Although this filter can process the noise-polluted signals, its major disadvantageous is in its required high calculation size, which limits its real-time functionality. The adaptive linear neural network (ADALINE) with a single neuron layer is introduced as a strong signal-processing tool (Bernard widrow, 1990). The utilization of this approach in real-time calculations such as harmonics (Dash, 1996), frequency (Dash, 1997; Sadinezhad, 2009), and symmetric components (Marei, 2004) estimation is developed due to its more simplicity and faster response to dynamic variations, in compare with other types of neural networks. The processing unit is introduced in order to estimate the fundamental frequency sequence components on the base on multi output ADALINE (MO-ADALINE) (Marei, 2004). In this paper, the harmonic components of each phase are extracted applying a single ADALINE unit to each phase. Applying a fuzzy regulator is proposed for selecting the optimum amount of ADALINE network learning factor. The zero, negative, and positive sequence

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of the subjected harmonic is extracted by its corresponding Fortescue transform. Therefore, applying Fortescue transform instead of MO-ADALINE decreases the calculation size and increases the responding time. It is also possible to calculate the sequence components of non-fundamental frequency harmonics by the developed Fortescue transform. In the next section, the mathematical relations of harmonics symmetric components are implied. In section 3, the structure of fuzzy ADALINE neural network for harmonics components is estimated. The proposed technique is evaluated in section 4 by simulating an artificial three-phase system and a sample distribution network. The conclusion is presented in section 5.

The Symmetric Components of Harmonics:

The existence of non-linear loads in the power system creates considerable amounts of harmonics components in current and voltage signals. The current and voltage unbalance is also created due to unbalance loads application or due to disproportionate three-phase current distribution among the single-phase consumers. Nowadays, the harmonics and the unbalancing are considered as the most important issues in power quality assessment. In this section, the formulation of harmonics symmetric components problem is mentioned. Therefore, the discrete form of single-phase current harmonical signal containing attenuated dc and noise parts is considered as follows:

$$i(k) = \sum_{l=1}^{N} |i_l| . \sin(l.\omega_1.k.\Delta t + \varphi_l) + A_{DC}.e^{-\beta.k.\Delta t} + \varepsilon \tag{1}$$

The sampling frequency is considered $f_s = \frac{1}{\Delta t}$.

In order to more simplification, the following is valid applying Taylor expansion on the damping part of dc signal:

$$A_{DC}.e^{-\beta k \Delta t} \approx A_{DC}(1 - \beta.k.\Delta t) \tag{2}$$

Applying trigonometric and after simplification, (2) can be expressed as vector multiplication as follows:

$$i(k) = \Phi(k).V(k) \tag{3}$$

The fuzzy elements of the above matrices are as follows:

$$\begin{aligned} \Phi(k) = [&\sin\theta, \cos\theta, ..., \sin l\theta, \cos l\theta, ..., \\ &\sin N\theta, \cos N\theta, 1, -k.\Delta t] \end{aligned} \tag{4}$$

$$V(k) = [v_1, v_2, ..., v_{2l-1}, v_{2l}, ..., v_{2N+1}, v_{2N+2}]^T \tag{5}$$

It is necessary to note that the order and the total number of harmonics that should be considered in inputs and weight vectors are determined due to the primitive conjectures from the existing harmonics or more exactly via the sampling and Fourier analysis of the signal in off-line mode. Therefore, the amplitude and the phase value of each harmonics component is obtained as follows after output contingency:

$$\begin{cases} |i_l| = \sqrt{v_{f,2l-1}^{\ 2} + v_{f,2l}^{\ 2}} \\ \varphi_l = \tan \dfrac{v_{f,2l-1}}{v_{f,2l}} \\ l = 1, 2, ...N \end{cases} \tag{6}$$

where $v_{f,2l-1}$ and $v_{f,2l}$ are the weight vector elements after contingency. The extracted amplitude and phase are then applied to calculate the three-phase system symmetric components.

Applying symmetric components technique for asymmetric three-phase systems analysis was introduced and presented by Charles Fortescue in 1918. The three-phase unbalance sinusoidal signal is considered as follows:

$$\begin{cases} i_a(t) = |i_{al}| . \sin(\theta + \varphi_a) \\ i_b(t) = |i_{bl}| . \sin(\theta + \varphi_b) \\ i_c(t) = |i_{cl}| . \sin(\theta + \varphi_c) \end{cases} \tag{7}$$

where $|i_{al}|$ and φ_a are amplitude and phase angle respectively and is the angular frequency of phase a. The indices related to phases b and c are specified the same.

The three-phase system is unbalance if the amplitudes of the phases are not similar or if the angle difference between the phases angle of the phases is not 120°. If so, the three-phase system symmetric components can be expressed in the following phasor mode. The following transform, which transforms the three-phase phasors in to the zero, negative, and positive sequences, is known as Fortescue transform as the following relation:

$$\begin{bmatrix} I^{\circ} \\ I^{+} \\ I^{-} \end{bmatrix} = \underline{A} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{8}$$

$$\underline{A} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{9}$$

where $a = e^{j\pi/3}$ and $a = e^{j2\pi/3}$.

If the three-phase signal is unbalanced, the zero and negative sequences are also created. Therefore, the symmetric components technique is an appropriate for unbalance rate of the three-phase systems.

II.1. The Developed Fortescue Transform:

In general, an unbalanced harmonical three-phase current signal is considered in discrete form as follows:

$$\begin{cases} i_a(k) = \sum_{l=1}^{i=N} \left| i_{al}(k) \right| . \sin(l\theta + \varphi_{al}) \\ i_b(k) = \sum_{l=1}^{l=N} \left| i_b(k) \right| . \sin(l\theta + \varphi_{bl}) \\ i_c(k) = \sum_{l=1}^{l=N} \left| i_{cl}(k) \right| . \sin(l\theta + \varphi_{cl}) \end{cases} \tag{10}$$

where $|i_{al}|$ and φ_{al} are the amplitude and angle of lth harmonic of phase a, respectively. The total number of harmonics is N. A similar indexing is accomplished for phases b and c. With some changes, the Fortescue transform results the symmetric components of the unbalanced three-phase system's non-fundamental harmonics (Alcantara, 2005; Arrillaga Jos, 2003) as follows:

$$\begin{bmatrix} I_l^{0} \\ I_l^{+} \\ I_l^{-} \end{bmatrix} = \underline{A} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{11}$$

$$\underline{A} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{12}$$

where $a = e^{j\pi/3l}$ and $a^2 = e^{j2\pi/3l}$ (l is the considered harmonics order)

I. Fuzzy ADALINE Neural Network:

The neural network capabilities such as data parallel processing, no requisition to complete, and accurate system information etc make it able to operate vastly in parameters estimation and system detection in engineering processes. The adaptive linear neural network possesses some unique features such as simple and single layer structure and fast responding capability to dynamic variations (Qian Ai, 2006).

The adaptive linear neural network (ADALINE) consists of p inputs, an approximation output, and its operation mechanism, the weighted sum of the inputs and a bias in each sampling step k. The input elements exist in input vectors (X) and the weighted elements lie in weight vector (W). The error signal is produced comparing the obtained estimated value with the actual value measured from the signal. The usual approach applied for weight coefficient updating operates based on the least means square of error known as Widrow-Hoff rule calculated as follows:

$$W(k+1) = W(k) + \Delta W(k) \tag{13}$$

$$\Delta W(k) = \frac{\alpha e(k) X(k)}{\lambda + X^T(k) X(k)} \tag{14}$$

where λ is a small real number to avoid facing zero value in denominator of the fraction. Further details about the application and convergence manner of ADALINE are reported in (Dash, 1996; Dash, 1997). In order to estimate the amplitude and the phase of the harmonics exist in a harmonical signal such as (1), X and W vectors are replaced by Φ and υ vectors of harmonics problem formulation. In conventional ADALINE systems, the convergence speed is determined selecting proper learning factor (α) which is a real number (0<α<2). Selecting small learning factor reduces the convergence speed of the algorithm as well as accuracy increase and convergence overshoot reduction of estimator output. Larger values selection reversely affects the ADALINE performance. Conciliation must be accomplished between speed and the accuracy of output convergence in selecting optimum learning factor. The fuzzy logic is applied in (Dash, 1998) for proper learning factor selection in each ADALINE iteration which would result in calculation bulk increase and practical implementation difficulty. Calculating the learning factor value in each ADALINE iteration, increases the processor calculating bulk and causes instantaneous oscillations in ADALINE estimator output. On the other hand, averaging error value in long interval for determining learning factor value leads to not appropriate and slow response to dynamic variations of signal. In this paper, applying fuzzy rules for learning factor updating are suggested to improve the performance of ADALINE neural network. Here, the proper time interval for optimum α value calculation is selected as 2mS. Therefore, the capability of implementing this algorithm on digital signal processors (DSP) and instant applications is well provided.

The block diagram of the proposed fuzzy ADALINE technique is illustrated in Fig. 1.

The inputs of this Mamdani fuzzy regulator are the abstract value of output error mean and its variation in mentioned interval (2mS). The output is updating factor of fuzzy ADALINE *α(Fuzzy)*.

The α value is obtained through Widrow-Hoff Rule fuzzy regulator as follows:

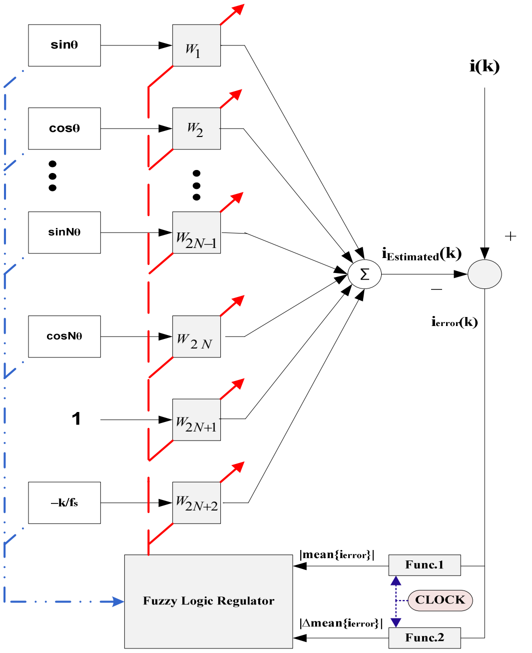

Fig. 1: The structure of the proposed fuzzy ADALINE

$$\alpha(FUZZY) = FUZZY \quad RULE(|mean\{e\}|,\ |\Delta mean\{e\}|) \tag{15}$$

The absolute value triangular belonging functions of the error mean and its variations along with its normalized range are considered with defined variables (S: small, M: medium, and B: big) as Fig 2-a and 2-b. The variations of error mean absolute derivative values are used as the second input of the fuzzy regulator for more simplicity since their magnitudes are too large.

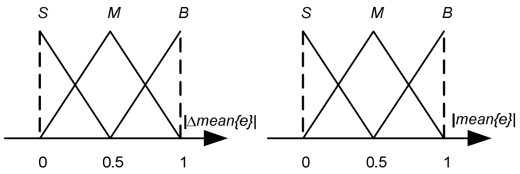

Fig. 2: a) The error mean absolute value belonging functions b) their variations.

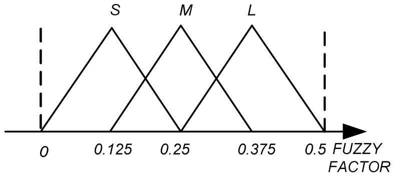

Fig. 3: The output of fuzzy regulator.

Nine fuzzy rules are defined (Table 1) for these fuzzy membership functions in inference stage and the membership function of fuzzy regulator output (Fig. 3) consists of three fuzzy sets (S: small, M: medium, and L: large).

Table 1: Used fuzzy rules

<table>
<tr><td colspan="2" rowspan="2">α(FUZZY RULE)</td><td colspan="3">|mean{e}|</td></tr>
<tr><td>S</td><td>M</td><td>B</td></tr>
<tr><td rowspan="3">|Δmean{e}|</td><td>S</td><td>S</td><td>M</td><td>M</td></tr>
<tr><td>M</td><td>S</td><td>L</td><td>L</td></tr>
<tr><td>B</td><td>M</td><td>M</td><td>L</td></tr>
</table>

The above inference approach is as max-min in which the minimum value is used in AND operator and maximum value is used as OR operator. In defuzzification stage, the center of average technique is applied. The fuzzy logic controller (FIS) of MATLAB software is utilized in the structure of ADALINE fuzzy regulator. The α level control carried out by fuzzy regulator is well illustrated in Fig. 4.

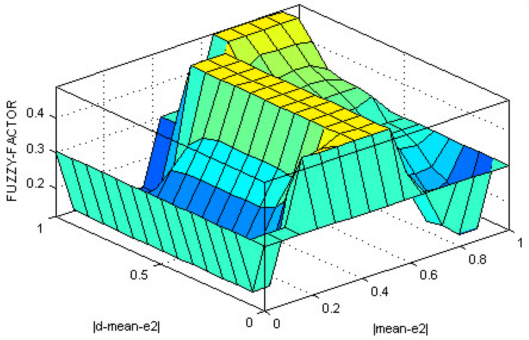

Fig. 4: The fuzzy regulator control level.

III. 1. Extracting harmonics symmetric components:

The diagram of proposed harmonics symmetric components estimator system relation is shown in Fig. 5.

As it is obvious, a Fortescue transform is used to estimate the fundamental frequency harmonics sequence while the commensurate improved Fourier transform is used for other harmonics sequence components as (11) and (12).

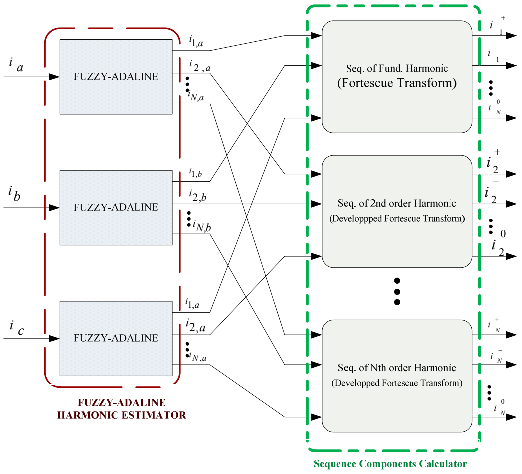

Fig. 5: The structure of the proposed harmonics symmetric components estimator system.

II. Simulations:

The proposed estimator system is simulated in MATLAB to evaluate the efficiency of the proposed approach in estimating harmonics symmetric components. In the first simulation the harmonics sequence components of an artificial unbalanced three-phase signal are extracted applying the proposed technique. In the second one, the current drained by the balance, unbalance, and switched nonlinear loads in a sample distribution system is applied to the proposed system. Simulation results show high capability of the proposed system in harmonical sequence components estimation. In the simulations, the ADALINE execution time interval is 0.5ms and optimum ADALINE learning factor is calculated by fuzzy regulator in 2ms.

IV.1. Simulation I: Artificial three-phase signal:

A three-phase artificial unbalance nonlinear signal is generated and applied to the proposed system. The components characters and the signal waveform are shown in Table 2 and Fig. 6, respectively.

Table 2: the characteristics of the sample artificial signal

Time(mS)		H.order	1st Order	3rd Order	7th Order
			I_2 (A) $\angle\varphi_2$ (deg.)	I_2 (A) $\angle\varphi_2$ (deg.)	I_2 (A) $\angle\varphi_2$ (deg.)
Pos. Seq.	t_1	0<t<51	10∠22.5°	2∠30°	1∠20°
	t_2	51<t	12∠10°	1∠30°	2∠10°
Neg. Seq.	t_1	0<t<51	3.33∠-30°	.5∠40°	0.7∠-10°
	t_2	51<t	3.33∠-10°	0.5∠-40°	0.5∠30°
Zero Seq.	t_1	0<t<51	2∠36°	0.2∠-10°	.2∠40°
	t_2	51<t	5∠45°	0.7∠-15°	1∠-40°

The sample signal is simultaneously applied to the proposed system and the processing unit structure. In fuzzy ADALINE, the 1st, 3rd, and the 7th harmonics orders are under consideration. The amplitude and the phase angle of the zero, positive, and the negative sequences of the fundamental frequency and other harmonics orders of the signal estimated by two different approaches are well shown in Figs 7-12.

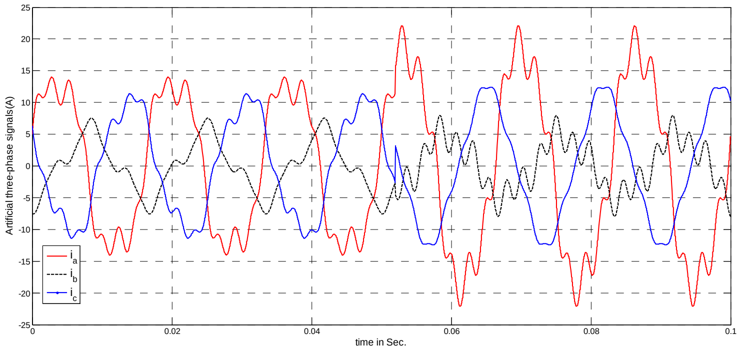

Fig. 6: The sample artificial harmonical three-phase signal.

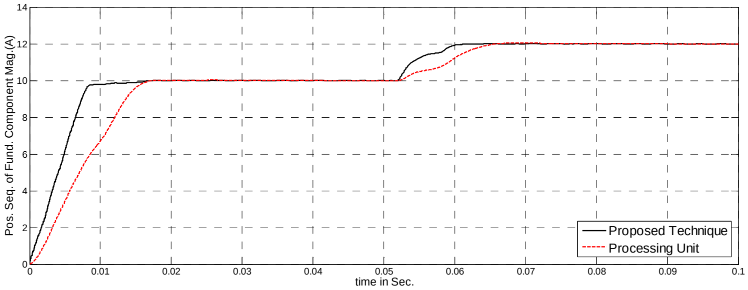

Fig. 7: The amplitude of the fundamental harmonic positive sequence component.

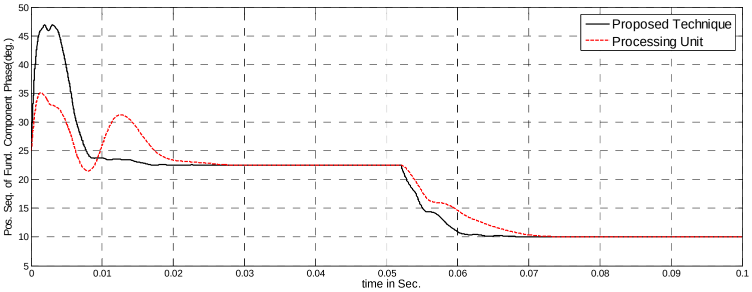

Fig. 8: The phase angle of the fundamental frequency positive sequence component.

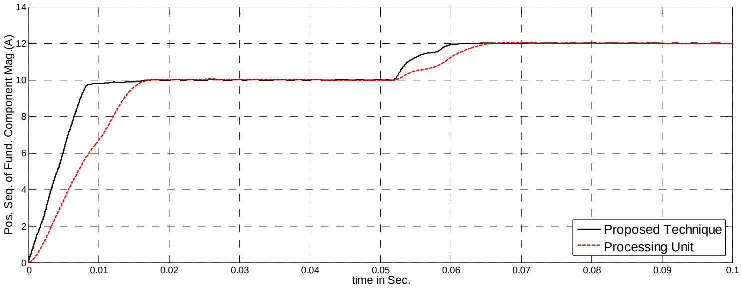

Fig. 9: The phase angle of the fundamental frequency negative sequence component.

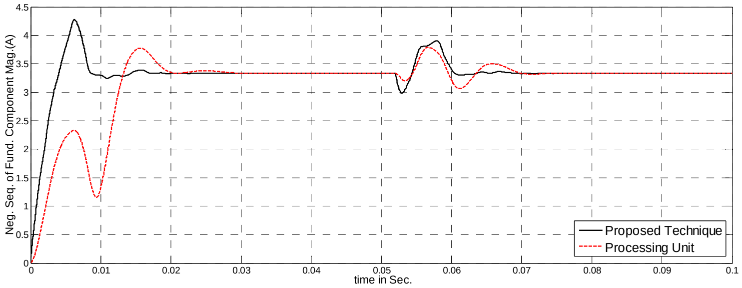

Fig. 10: The amplitude of the fundamental harmonic negative sequence component.

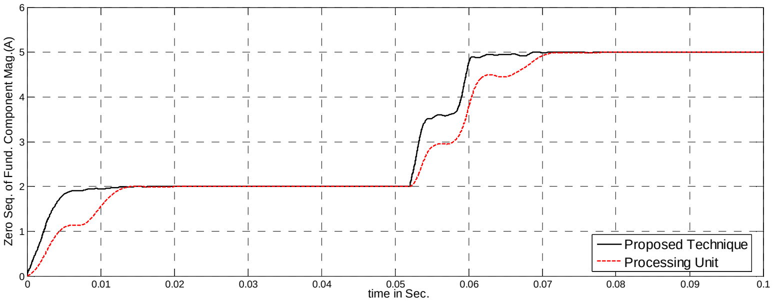

Fig. 11: The amplitude of the fundamental harmonic zero sequence component.

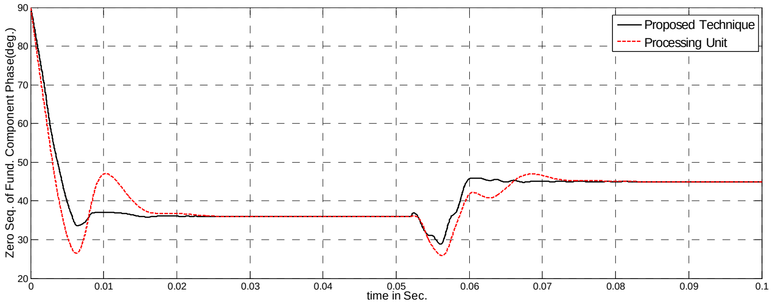

Fig. 12: The phase angle of the fundamental frequency zero sequence component.

The above figures show the higher responding speed and lower overshoot of the proposed technique in compare with the processing unit approach. An advantageous of the proposed technique falls in the ability of harmonical sequence components estimation. The amplitude and the phase-angle of signal's 3rd order harmonic sequences are shown in Figs. 13-14, respectively.

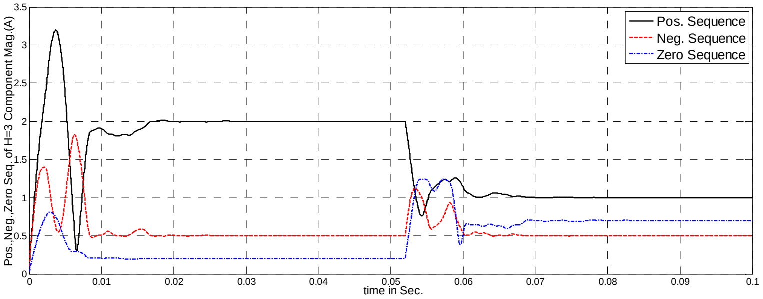

Fig. 13: The amplitude of the 3rd order harmonic sequence components.

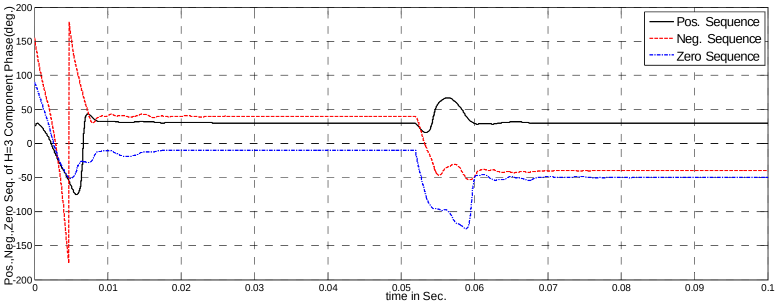

Fig. 14: The phase angle of the 3rd order harmonic sequence components.

Figs. 15-16 show respectively the amplitude and the phase angle of the three-phase signal (abc) fundamental frequency harmonics before Fortescue transform application. Considering the angular frequency of the artificial signal as θ, the abc form of the mentioned signal is calculated by (10) and is illustrated in Fig. 17.

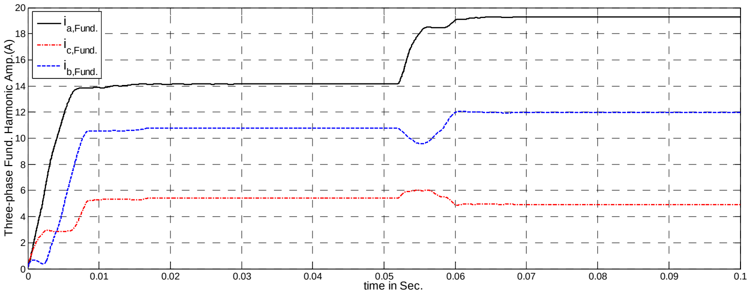

Fig. 15: The amplitude of fundamental harmonical three-phase signal.

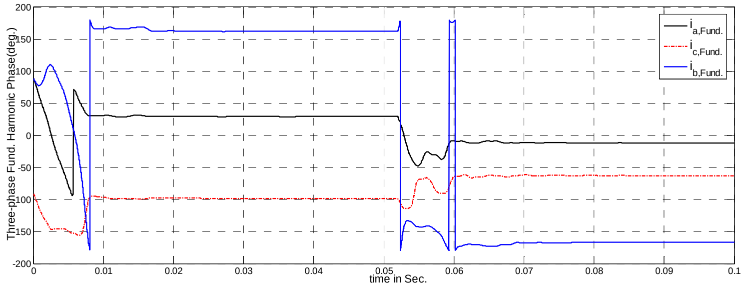

Fig. 16: The phase angle of fundamental harmonical three-phase signal.

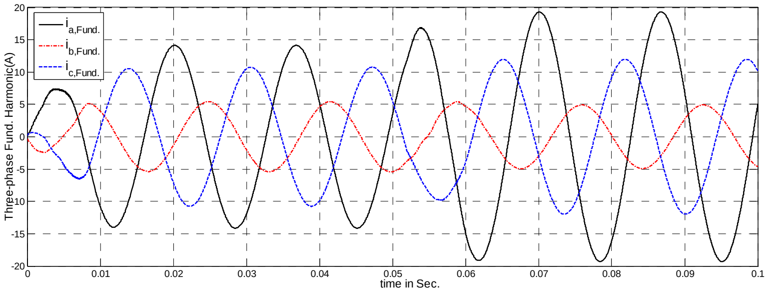

Fig. 17: Fundamental harmonical three-phase signal.

Investigating the estimated output through the proposed system in sample artificial three-phase signal components estimation depicts that the proposed technique is considerably flexible in fundamental harmonics amplitude/angle components estimation and is flexibly able to calculate the fundamental and harmonical frequency symmetric components.

The fuzzy regulator can be neglected and an ADALINE structure can be use in each phase if the processor speed limitation in proposed technique implementation exists and ADALINE speed improving is not under consideration.

IV.2. Simulation II: The sample distribution network:

As Fig. 18, the sample distribution system feeds balance, unbalance, and nonlinear loads. The network features, loads, and their switching scenario are well detailed in appendix 1.

The three-phase network voltage in the point of common connection and the loads drained three-phase current are shown in Figs. 19-20, respectively. It is important to note that there is no compensation device in this distribution system, the load current (i_L) is the same as the source current (i_S). The 1st, 3rd, 7th, 11th, and the 19th harmonic orders are under consideration in fuzzy ADALINE structure.

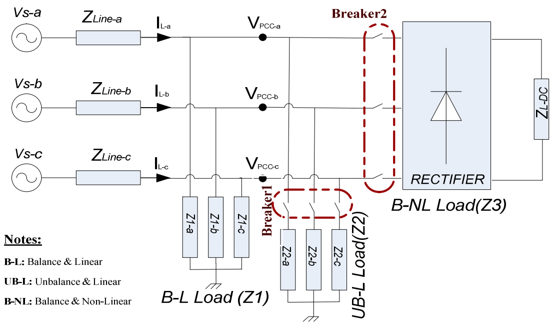

Fig. 18: Sample distribution network.

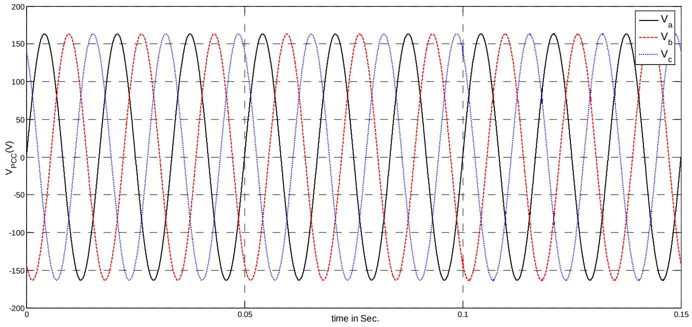

Fig. 19: The voltage of the point of common connection.

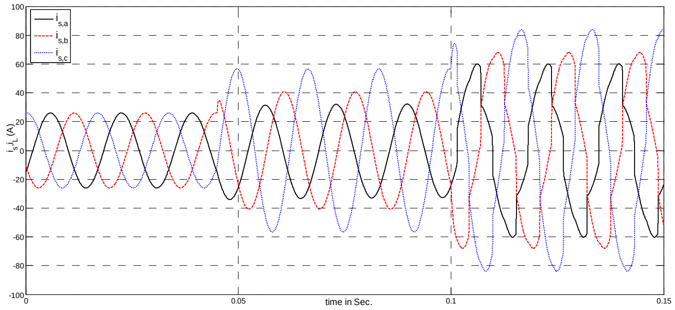

Fig. 20: The load three-phase current (drained from the network).

Phase locked Loop:

The instant value of three-phase system angular frequency (θ) is required in order to carry out the amplitude and phase angle estimation of the harmonics in ADALINE system especially in (3) and (4). Therefore, θ is obtained from a reference signal (usually the system voltage). The phase locked loop (PLL) is a system generates an output signal in proportion with the phase angle of the reference signal (Karimi-Ghartemani, 2006). The output of PLL responds to the phase angle variations and reference signal frequency in a way that the correct θ instant value is continuously generated. In this simulation, a PLL with point of common connection reference voltage is used.

The amplitude and the phase angle of load current fundamental harmonics zero, negative, and positive sequences estimated via the proposed algorithm are illustrated in Figs 21-22, respectively.

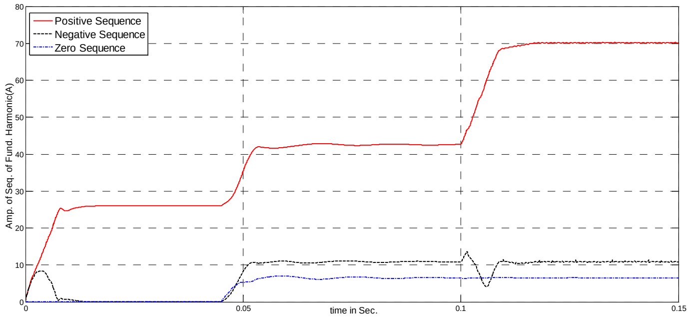

Fig. 21: Fundamental harmonic sequences amplitude.

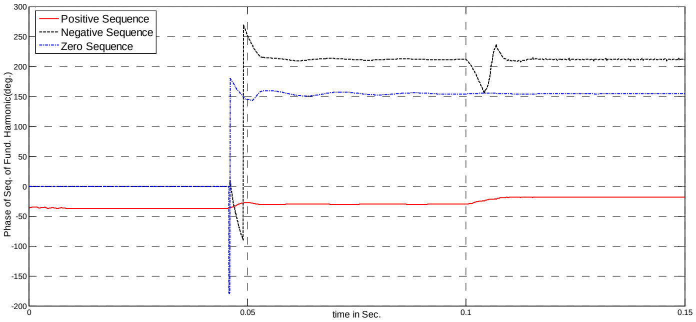

Fig. 22: Fundamental harmonic sequences phase angle.

In some applications such as compensation signal generation in custom power devices, the three-phase form of fundamental harmonic positive sequence signal is required which can be calculated by applying phase angle instant value resulted from PLL output to (10) and is shown in Fig. 23 along with i^{+}_{Fund} .

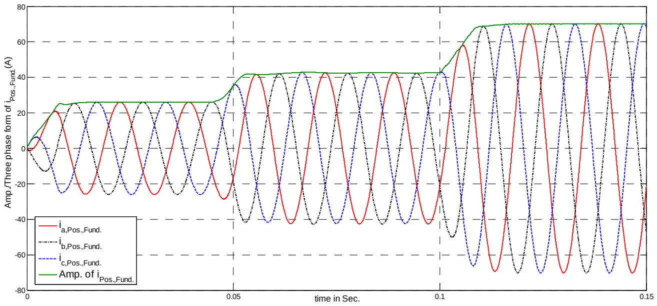

Fig. 23: The positive sequence amplitude of fundamental harmonic and its three-phase form.

The a phase voltage magnitude in the point of common connection ($V_{PCC,a}$), load current (i_a) and the positive sequence component current of load current fundamental frequency harmonics i^{+}_{Fund} are shown in Fig. 24.

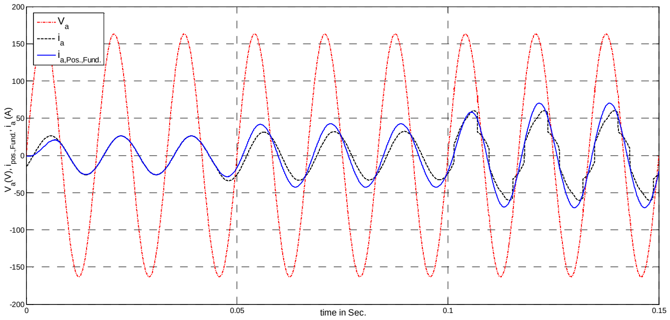

Fig. 24: *a* phase values: voltage, load current, load current fundamental harmonic positive sequence.

According to the switching scenario of this sample distribution network, the balance Z_1 is the only existing load during the first time interval. Here, the load current equals to that of the positive sequence and there is no zero and negative sequence current (Fig. 21, 24). In t=45ms, the Z_2 unbalance load enters the network. Here, the negative and the zero sequences are also detected (the system is four wire). In t=100ms, the Z_3 nonlinear balance load enters and makes the load current waveform harmonical and distorted. The proposed technique is able to estimate the sequence components of other harmonics as well as estimating the sequence components of the fundamental frequency. As an example, the load current i_5^-, i_5^0, and i_7^+ harmonic currents sequence components are illustrated in Table 3.

Table 3: harmonical symmetric components

Time Component		0<t<45mS	45<t<100mS	100mS<t
i_s^-	Amp.(A)	0	0	6.5
	Ph.(deg.)	0	0	164
i_s^0	Amp.(A)	0	0	0.1
	Ph.(deg.)	0	0	-125
i_s^+	Amp.(A)	0	0	3.8
	Ph.(deg.)	0	0	160

Conclusion:

In this paper, the new three-phase signal harmonics symmetric components estimation technique based on the fuzzy ADALINE neural network and improved Fortescue transform is proposed. The amplitude and the phase angle components of harmonics exist in each phase are estimated by a fuzzy ADALINE unit. The three-phase phasors of each harmonic is applied to a common or improved Fortescue unit in order to extract simultaneously the fundamental or non-fundamental harmonic symmetric components. The simulation results well show the appropriate operation of the proposed technique in accurate and fast estimation of symmetric components of an artificial three-phase signal fundamental and other frequency harmonics. The results show that the proposed technique can be applied in a sample three-phase system and can be utilized in power quality monitoring and online applications such as reference signal generation in power quality compensating devices.

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