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FUZZY MEASUREMENTS OF SYMMETRICAL COMPONENTS FOR POWER SYSTEM CONTROL

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Abstract

The symmetrical components are an effective tool for the analysis of the unsymmetrical fault in the power systems. Also, it can be used as an indication to abnormal normal operation of power systems. This paper presents the application of fuzzy system to measure the symmetrical components of a power system for control and protection. The samples for the symmetrical components are obtained using the symmetrical transformation matrix in the time domain. Then the problem of the symmetrical component parameters is formulated as a linear fuzzy regression problem to estimate the fuzzy parameters of each component from the available samples. Two models are discussed in this paper, while in the first model, we assume that the data samples are non-fuzzy, and the model coefficients are fuzzy. In the second model, we assume the data samples are fuzzy and the model parameters are also fuzzy. The simplex-based linear programming method is used to solve the resulting problems. Simulated and actual recorded data are presented in the paper.

1. Introduction

Symmetrical components are widely used in analysis of unsymmetrical faults in a power system, as well as, the analysis electrical machines operation in unbalanced voltage or current. Power quality problems can result from

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unbalances in either the system load or the system components. Information on the symmetrical components is extensively used in digital protection of power system components. As such an accurate and fast algorithm is needed to measure the symmetrical components especially from a harmonic polluted unbalanced three-phase system, distorted signals.

The unbalances either in the system load or the system components can cause power quality problems. These unbalances can result in overheating of system component [11]. Appropriate system voltage and current measurements combined with symmetrical component can determine the source of these system unbalances.

Reference [4] presents an algorithm for symmetrical components calculation in power system relaying signal. The block pulse functions (BPF) based algorithm is employed to compute the fundamental frequency components of the distorted 3-phase power system signals. The well-known symmetrical component transformation is then applied to obtain the sequence components. Reference [6] presents methods for online calculation of the phasors of symmetrical components from the complex space-phasor. The methods combine the suppression of some of higher frequencies and the separation of symmetrical components. The methods in this reference are in the frequency domain, and need a calculation of complex phasors to estimate the components. Reference [2] presents a digital filter based on digital signal processing that capable of extracting the symmetrical component of the line-to-line voltages of an AC power supply. It basically extracts the fundamental voltage components and then calculating the symmetrical components. A simplified radix-2 discrete Fourier (DIF) and fast Fourier transforms (FFT) is used to extract the time-varying fundamental phasors. Reference [1] presents a procedure for deriving symmetrical current components based upon the magnitude of the three phase currents in a system. By measuring the magnitudes of the three phase currents, the protection relay can store curve breakpoints such that true positive sequence, negative sequence and unbalance information can be obtained.

Estimation of the current and voltage symmetrical components in a three-phase electrical network is carried out using a state observer [8]. The state observer algorithm is based on the recursive model of the current and voltage generation process in a three-phase power system in which the orthogonal phasors are used as the model state variables. The state observer can be used as the fast current and voltage symmetrical component estimator in digital power protection systems. Reference [12] presents the implementation of the least errors square parameter estimation algorithm for measuring the symmetrical components for power system protection. The proposed algorithm uses directly the samples of the three phase voltages. The symmetrical components are modeled in the time domain. A model that enables linear Kalman Filtering (KF) to be applied for the direct estimation of symmetrical components in unbalanced three-phase system is applied in reference [13]. In this algorithm the zero sequence components is estimated first, and then filtered out from the available samples for the three phases, then the KF algorithm is applied to extract the negative and positive components from these samples.

A microprocessor based algorithm for the calculation of symmetrical components of a three-phase system is presented in reference [10], the algorithm is based on fast Walsh-Hadamard transform, the symmetrical components can be calculated in ¾th of cycle after fault occurrence. Reference [3] presents an approach to estimate the symmetrical and α-β components of the voltage and current signals of power distribution network using Fourier Linear Combiners (FLC). The weights of the combiner are adapted using a fuzzy logic based algorithm obtained from the error covariance. The non-recursive Newton type algorithm is extended with the second stage algorithm for symmetrical components calculation from the estimated fundamental phasors of three-phase signals is implemented in reference [14]. The algorithm is not sensitive to power system frequency changes and to harmonic distortion of input signals.

Reference [15] reports new software developments for symmetrical components estimation. Non-recursive Newton-type algorithm is extended with the second stage algorithm for symmetrical components calculation from the estimated fundamental phasors of three-phase signals (arbitrary voltages or currents). The algorithm is not sensitive to power system frequency changes and to the harmonic distortion of input signals. The algorithm is tested through computer simulations and by using laboratory obtained input signals and those recorded in the real distribution network.

Reference [7] introduces a novel adaptive linear combiner (ADALINE) structure for symmetrical components estimation. This structure is capable of dealing with multi-output systems for parameter tracking/estimation rather than the existing ADALINE, which deals only with single output systems. As the new topology deals with Multi-Output systems, it is called MO-ADALINE. Moreover, the paper presents a new processing unit, which can estimate symmetrical and harmonic components from the measured current signals. The advantages of this proposed unit are its independence of the voltage waveform and its ability to give information about the reactive component of the resolved current.

A complex band pass filter is presented in reference [5]. This complex band pass filter can correctly extract the phasor of the fundamental component and symmetrical components in voltage or current waveforms and then accurately estimate their instantaneous amplitude, phase angle, and frequency, even encountering various power disturbances. Further, a recursive algorithm is also developed for the complex band pass filtering that updates current filtering output only using several previous sample values and filtering outputs. This attribute greatly reduces the computational complexity of complex band pass filtering, which is the weakness of the continuous wavelet transform based on the well-known Morlet Wavelet. Thus, this recursive algorithm is highly desirable for real-time applications.

This paper presents the application of fuzzy system to measure the symmetrical components of a power system. The samples for the symmetrical components are obtained using the symmetrical transformation matrix in the time domain. Then problem to estimate the fuzzy parameters of each component from the available samples is formulated as a linear fuzzy regression. Two models are discussed in this paper, while in the first model, we assume that the data samples are non-fuzzy, and the model coefficients are fuzzy. In the second model, we assume the data samples are fuzzy and the model parameters are also fuzzy. The simplex-based linear programming method is used to solve the resulting problems. Simulated and actual recorded data are presented in the paper.

2. Modeling the Three-Phase Signal

Given m samples of the three-phase voltage or current signal, sampled from harmonics or noisy polluted environment. It’s required determining the positive, negative and zeroing symmetrical components of the fundamental components of the voltage or current waveforms, for power quality analysis or power system protection. The positive, negative and zero sequence components of a three-phase system, voltage or current, can be written as [4].

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}. \tag{1}$$

The above three equations are well-known equations for the power engineers working in the analysis of unsymmetrical faults in power systems. Where the operator a is defined as:

$$a = 1\angle 120^\circ,\ a^2 = 1\angle 240^\circ.$$

The above equations are also valid for the symmetrical components of the unbalanced three phase currents. At a sample k, the above equations can be written in the time domain as:

$$V_{a1}(k) = \frac{1}{3}[V_a(k) + V_b(k + \theta_1) + V_c(k + \theta_2)], \tag{2}$$

$$V_{a2}(k) = \frac{1}{3}[V_a(k) + V_b(k + \theta_2) + V_c(k + \theta_1)], \tag{3}$$

$$V_{ao}(k) = \frac{1}{3}[V_a(k) + V_b(k) + V_c(k)], \tag{4}$$

where θ_1 and θ_2 are the number of samples equivalent to the angles 120° and 240° respectively. For the fundamental components, these are equal to $\theta_1 = \frac{f_s}{3f_o}$, $\theta_2 = \frac{2f_s}{3f_o}$, where f_s is the sampling frequency, f_o is the waveform fundamental frequency, 50 or 60 Hz. The only restriction on equations (2) to (4) is that θ_1 and θ_2 must be integral numbers, so that the sampling frequency should be chosen to produce these integral numbers, which can be done easily, since most of the A/D converters have a wide range of sampling frequencies. Note that, for the positive, negative and zero sequence components of harmonics that contaminate the waveforms, f_o, in this case, has a value of N times the fundamental frequency, where N is the harmonic order.

Now, the problems turns out to be: given m samples of the voltage or current waveform, sampled at a pre-selected rate $\Delta T = 1/f_s$, then using equations (2) to (4), m samples for the positive, negative and zero sequence components would be obtained. Having obtained this m samples for the symmetrical components, then the magnitude and phase angle of each component can be obtained as:

2.1. The positive sequence component

The positive sequence voltage signal can be written in the time domain as a fuzzy equation given by:

$$v_{a1}(t) = \underline{X}_{a1} \sin \omega t + \underline{Y}_{a1} \cos \omega t, \tag{5}$$

where we define the fuzzy number underlined above as:

$$\underline{X}_{a1} = V_{a1} \cos \phi_{a1} \tag{6}$$

and

$$\underline{Y}_{a1} = V_{a1} \sin \phi_{a1} \tag{7}$$

In the above equations V_{a1} and ϕ_{a1} are the fuzzy amplitude and fuzzy phase angle of the positive sequence component, respectively. Each fuzzy number stated above is assumed to have a certain middle p_{a1} and a certain spread c_{a1}. On other words, we assume a triangular membership function. Thus equation (1) can be written as:

$$V_{a1}(t) = (p_1, c_1)_{a_1} \sin \omega t + (p_2, c_2)_{a_1} \cos \omega t. \tag{8}$$

1. The case of non-fuzzy data [9]

Assume that $V_{a1}(t)$ are crisp samples, but the coefficients X_{a1} and X_{a2} are fuzzy parameters. Then, the fuzzy regression optimization problem turns out to be

Given m crisp samples of the positive sequence component, it is required to estimate the fuzzy parameter $\underline{X}_{a1}$ and $\underline{Y}_{a1}$ that minimize the spread of each measurement sample, subject that the solution obtained is included in the membership function. Mathematically, this can be expressed as:

Minimize

$$O = \sum_{j=1}^{m} \{c_1[\sin \omega t]_j + c_2[\sin \omega t]_j\}. \tag{9}$$

Subject to satisfying two constraints in each measurement sample given as:

$$(V_{a1}(t))_j \geq p_1[\sin \omega t]_j + p_2[\cos \omega t]_j - (1-\lambda)c_1[\sin \omega t]_j$$
$$- (1-\lambda)c_2[\cos \omega t]_j; \quad j = 1, \dots, m \tag{10}$$

and

$$(V_{a1}(t))_j \leq p_1[\sin \omega t]_j + p_2[\cos \omega t]_j + (1-\lambda)c_1[\sin \omega t]_j$$
$$+ (1-\lambda)c_2[\cos \omega t]_j; \quad j = 1, \dots, m, \tag{11}$$

λ is the degree of fuzziness. Equation (10) and (11) simply state that the optimal fuzzy solution obtained must be included in the membership function. Now, the problem formulated in equations (9) to (11) is a linear programming optimization problem, and can be solved using the simplex method based linear programming.

Having identified the median $(p_1, p_2)_{a1}$ and the spread $(c_1, c_2)_{a1}$, then the median and spread of the positive sequence component can be obtained, by performing fuzzy number operation as:

$$V_{a1}{}^2 = [(p_1, c_1)\cdot(p_1, c_1) + (p_2, c_2)\cdot(p_2, c_2)]. \tag{12}$$

This gives

$$V_{a1} = [\{\min(p_1\cdot p_1, p_1\cdot c_1, c_1\cdot p_1, c_1\cdot c_1) + \min(p_2\cdot p_2, p_2\cdot c_2, c_2\cdot p_2, c_2\cdot c_2)\},$$
$$\max(p_1\cdot p_1, p_1\cdot c_1, c_1\cdot p_1, c_1\cdot c_1) + \max(p_2\cdot p_2, p_2\cdot c_2, c_2\cdot p_2, c_2\cdot c_2)\}^{1/2}. \tag{13}$$

The above equation can also be written as

$$V_{a1} = [(p_1^2, p_2^2)^{1/2}, (c_1^2, c_2^2)^{1/2}] \tag{14}$$

and

$$\tan \phi_{a1} = (p_2, c_2)\cdot(1/c_1, 1/p_1)$$
$$\phi_{a1} = [\tan^{-1}(p_2/c_1), \tan^{-1}(c_2/p_1)]. \tag{15}$$

The first term in equation (14) gives the amplitude of the positive sequence voltage, while the second term gives the spread of this amplitude. Meanwhile, the first term in equation (15) gives the phase angle of the symmetrical component, while the second term is the spread of this angle. In the above equation, we assume that $0 \notin (p_1, c_1)$, $0 \notin (p_2, c_2)$, $p_1 < c_1$ and $p_2 < c_2$.

2. The case of fuzzy data [15]

If the samples are containing imprecise measurements the output, in this case, is best represented by a fuzzy number as $V_{a1} = (m_{a1}, e_{a1})_j$ where m_{a1} is the middle value and e_{a1} represents the ambiguity in the output. The objective function to be minimized is similar to that given in equation (9) but subject to the following constraints:

$$(m_{a1})_j - (1-\lambda)e_{a1} \geq p_1[\sin \omega t]_j + p_2[\cos \omega t]_j - (1-\lambda)c_1[\sin \omega t]_j - (1-\lambda)c_2[\cos \omega t]_j; \quad j = 1, \ldots, m \tag{16}$$

and

$$(m_{a1})_j + (1-\lambda)e_{a1} \leq p_1[\sin \omega t]_j + p_2[\cos \omega t]_j + (1-\lambda)c_1[\sin \omega t]_j + (1-\lambda)c_2[\cos \omega t]_j; \quad j = 1, \ldots, m. \tag{17}$$

Having identified the parameters of the fuzzy coefficients, middle and spread, then the amplitude and phase angle of the component can be determined using equations (13) and (15).

The above derivation is also valid for the negative and zero sequence components. Thus, formulate the linear fuzzy regression problem for the negative and zero symmetrical components are not presented here. What you need is just replacing, in the above equations, the subscript $a1$ by $a2$ to obtain the formulas of negative sequence, and $a0$ to obtain the formulas of zero sequence components and using the samples for each component to estimate the corresponding fuzzy parameters.

3. Computer Experiments

3.1. Non-fuzzy data

The results for a simulated example from the area of power system analysis are given in this section. The three phases are highly unbalanced voltages given in p.u. as:

$$V_a = 1.6\angle 34.5^\circ,\ V_b = 0.851\angle -1203^\circ,\ V_c = 0.52\angle{-169}^\circ \text{ p.u.}$$

The three phase unbalanced voltages are sampled at $F_s = 6000$ Hz, and a number of samples equals 20 is used (1/6 cycle @ 50 Hz or 1/5 cycle @ 60 Hz). Using the conventional symmetrical component theory, the symmetrical three components are

$$V_{a1} = 0.9\angle 30^\circ,\ V_{a2} = 0.6\angle 45^\circ \text{ and } V_{a0} = 0.2\angle 15^\circ \text{ p.u.}$$

To estimated the fuzzy parameters of the symmetrical components. The simplex based on linear programming method is used to solve the resulting linear optimization problem. The fuzzy model parameters for each component are given as:

- +ve sequence:

$$\underline{X}_{a1} = (0.77954,\ 0),\ \underline{Y}_{a1} = (0.45113,\ 0)$$

- –ve sequence:

$$\underline{X}_{a2} = (0.42450,\ 0),\ \underline{Y}_{a2} = (0.42400,\ 0)$$

- Zero sequence:

$$\underline{X}_{a0} = (0.11489,\ 0),\ \underline{Y}_{a0} = (0.03111,\ 0).$$

It can be noticed that the coefficients are non-fuzzy coefficient.

Using equations (13) to (15), we obtain

$$V_{a1} = 0.9\angle 30^\circ,\ V_{a2} = 0.6\angle 45^\circ,\ V_{a0} = 0.20\angle 15^\circ,$$

which are the same results obtained using the conventional symmetrical components theory. Indeed, in a very short data window size, the proposed technique produces very accurate estimate.

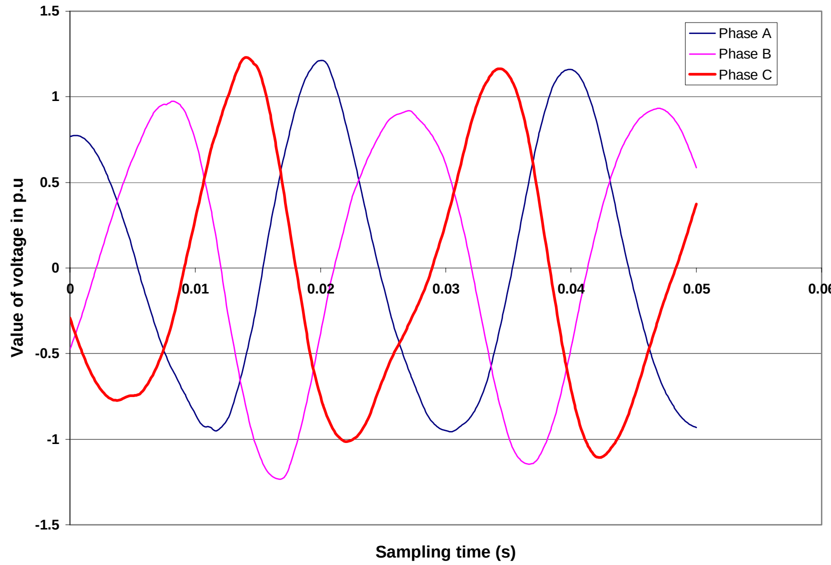

Figure 1. Three-phase voltage waveform during switching on.

The proposed algorithm is tested with actual recorded data for a three-phase voltage signal. The signal waveform is shown in Figure 1, the positive, negative and zero sequence components are estimated using equations (2) to (4). In this section we assume that these components are non-fuzzy. The estimated fuzzy model parameters for each component when the sample frequency is 1500 Hz and a number of samples equal 10 are:

- +ve sequence component

$$\underline{X}_{a1} = (0.0341,\ 0.1253),\ \ \underline{Y}_{a1} = (0.6752,\ 0.17193)$$

- – ve sequence component

$$\underline{X}_{a2} = (0.0,\ 0.25),\ \ \underline{Y}_{a2} = (0.0733,\ 0.0032)$$

- zero sequence component

$$\underline{X}_{a0} = (0.0,\ 0.0),\ \underline{Y}_{a0} = (0.0,\ 0.0).$$

It can be noticed that the positive sequence is a fuzzy component as well as the negative sequence. However, there is no zero sequence, since the three phases during this data window size are balanced. Using equations 13 to 15, we can easily calculate the symmetrical component magnitudes as

$$V_{a1} = (0.68675,\ 0.17527),\ \ V_{a2} = (0.0733,\ 0.25) \text{ and } V_{a0} = (0,\ 0).$$

If the data window size is increased to 15 samples at the same sampling frequency, the short circuit period is included in the calculation; the following values are obtained for each symmetrical component

- +ve sequence component

$$\underline{X}_{a1} = (0.0,\ 2.7933),\ \ \underline{Y}_{a1} = (0.9496,\ 0.0)$$

- –ve sequence component

$$\underline{X}_{a2} = (0.1359,\ 0.55175),\ \ \underline{Y}_{a2} = (0.07839,\ 0.0)$$

- zero sequence component

$$\underline{X}_{a0} = (0.0,\ 1.189),\ \ \underline{Y}_{a0} = (0.1264,\ 0.0).$$

Using equations (13) to (15) gives the following results

$$V_{a1} = (0.9496,\ 2.793),\ \ V_{a2} = (0.1359,\ 0.5573) \text{ and } V_{a0} = (0.1264,\ 1.1893).$$

From these results, one can notice that the data window size has a great effect on the estimated parameters. Indeed, that is true; if we examine carefully Figure 1 we can notice that the voltage waveforms having different distortion from one data window size to the other.

4. Conclusions

In this paper we present the application of fuzzy systems to measure the symmetrical components of a power system for control and protection. The symmetrical component samples are obtained using the symmetrical component transformation matrix in the time domain. Then the problem of the symmetrical component parameters is formulated as a linear fuzzy regression problem to estimate the fuzzy parameters of each component from the available samples. Two models are discussed in this paper, while in the first model, we assume that the data samples are non-fuzzy, and the model coefficients are fuzzy. In the second model, we assume the data samples are fuzzy and the model parameters are fuzzy as well. The simplex-based linear programming method is used to solve the resulting problems. Simulated and actual recorded data are presented in the paper. It has been found that for the simulated data, the sampling frequencies as well as the data window size have no effect on the estimated parameters. However they have a great effect on the estimated parameters for the actual recorded data as those shown in Figure 1.

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