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COMPARISON OF PRONY AND ADALINE METHODS IN INTER-HARMONIC ESTIMATION

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Abstract: Especially in energy and power systems, harmonic estimation has crucial role. Many techniques developed in the subject of harmonic and inter-harmonic estimation. These techniques and methods include mathematical transformation (Fourier, Hartley, Hilbert-Huang, etc.) filters (adaptive, Kalman, etc.) and parametric methods (Prony, ADALINE, MUSIC, etc.) In realized study, performance of ADALINE and Prony methods are investigated in terms of harmonic and inter-harmonic prediction capability. Required data for simulations are produced from P&O MPPT algorithm for photovoltaic systems. Therefore, this model gives opportunity to try compared methods according to different harmonic intensity (closeness of harmonics to each other). At the result of different simulations, it is observed that Prony method is more preferable for low number of data and ADALINE produces more successful results than Prony method if there is high number of data and selection of high neuron size relatively.

Keywords: Inter-harmonic, Prony method, ADALINE.

Ara Harmonik Kestiriminde Prony ve Adaline Yöntemlerinin Karşılaştırılması

Öz: Özellikle enerji ve güç sistemlerinde harmonik kestirimi, önemli rol oynamaktadır. Harmonik ve ara harmoniklerin kestirimi konusunda birçok yöntem ve teknik geliştirilmiştir. Bunlar arasında matematiksel dönüşümler (Fourier, Hartley, Hilbert-Huang vb.), filtrelemeler (adaptif, Kalman vb.) ve parametrik yöntemler (Prony, ADALINE, MUSIC vb.) yer almaktadırlar. Gerçekleştirilen çalışmada; Prony ve ADALINE yöntemlerinin ara harmonik kestirimindeki performansları incelenmiştir. Benzetimler için gerekli veriler, fotovoltaik sistemler için uygulanan P&O MPPT algoritmasından üretilmektedir. Böylece bu model; karşılaştırılan yöntemleri farklı harmonik içerik yoğunlukları (harmoniklerin birbirine yakınlıkları) açısından deneme olanağı vermektedir. Farklı benzetimlerle yapılan karşılaştırmalar sonucunda, veri sayısının düşük olduğu durumlarda Prony yönteminin daha tercih edilebilir olduğu; yüksek olduğu ve görece olarak çok sayıda nöronun kullanıldığı durumlarda da ADALINE yönteminin Prony yönteminden daha başarılı sonuçlar verdiği görülmüştür.

Anahtar Kelimeler: Ara harmonik, Prony yöntemi, ADALINE.

1. INTRODUCTION

In power systems, the harmonic problem has existed since the emergence of alternating current (AC) systems. Many studies have been proposed for definition and determination of this problem since beginning of 20th century (Bedell and Mayer, 1915; Bedell and Tuttle, 1906; Frank, 1910; Heartz and Saunders, 1954). Due to the fact that linear systems were generally used in the early stages of power systems, occurred harmonics were multiples of main harmonic

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(fundamental harmonic) and revealing these types of harmonics could easily be performed with commonly known techniques such as Fourier Transform. For this reason, in the early period, harmonic analysis was not a conspicuous issue. But at the end of 20^{th} century, inter-harmonics emerged in power systems depending on the development of semiconductor technology and its technological applications which include non-linear loads such as converters, inverters, cycloconverters, rectifiers, etc. Inter-harmonics which were produced by non-linear loads couldn't be determined with conventional harmonic analysis methods. This situation gave rise to many researches about inter-harmonic determination methods.

Filtration and elimination of harmonics in power systems are very important in order to increase power quality factor. They are one of the reasons for creation of many methods in recent years (Bollen and Gu, 2006; Chang and Chen, 2010; Duhamel and Vetterli, 1990; Gonen, 1984, Jain and Singh, 2011; Kay and Marple, 1981; Robinson, 1982; Singh, 2009; Thomson, 1982). The other necessity of filtration and elimination of inter-harmonics is protecting circuits from resonance effect which is not foreseen with theoretical calculation according to conventional frequency analysis techniques. From classical perspective, necessary preventions are considered in design stage with taking into account just only integer multiples of main harmonic. Passive elements may destroy circuitry because of not consideration of resonance effect in non-integer multiples of main harmonic. These types of situations can be avoided with determination and filtration methods during system operation. Besides, except inter-harmonic determination algorithms, new models which try to explain how inter-harmonics occur are proposed to literature in recent years (Sangwongwanich et al., 2018; Testa et al., 2007).

Inter-harmonic determination methods could be separated in three classes: parametric methods, non-parametric methods and hybrid methods (Figure 1) (Jain and Singh 2011). Parametric methods define signal parameters (amplitude, phase and frequency) with mathematical equation and solve this equation stochastically or deterministically (such as MUSIC, ADALINE, Kalman filter, ESPRIT, Prony method etc.) (Chang et al., 2009; Dash et al., 1999; Kalman, 1960; Prony, 1795; Roy and Kailath, 1989; Schmidt, 1986). On the other hand, non-parametric methods are such algorithms that could decompose signal's attributes (amplitude, phase and frequency) without depending on mathematical equations (such as discrete Fourier transform, Hilbert-Huang transform, wavelet transform etc.) (Cooley and Tukey, 1965; Grossmann and Morlet, 1984; Huang et al., 1998; Mallat, 1989; Winograd, 1976). Lastly, hybrid methods are combination of parametric and non-parametric methods for determining signal components. The most important feature of hybrid methods are that their capability to blend advantages of parametric and non-parametric methods and creating more robust method. There are many hybrid methods which are created by combining parametric and non-parametric methods (Bettayeb and Qidwai, 2003; Hostetter, 1980; Mishra, 2005; Tarasiuk, 2004).

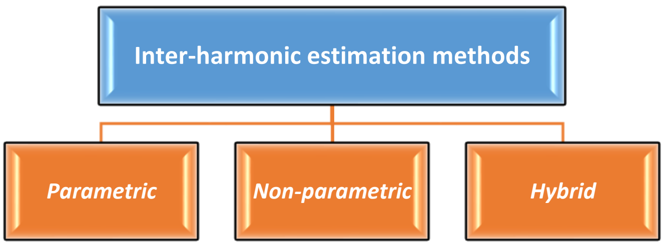

Figure 1:
Classification of inter-harmonic estimation methods

In this study, Prony and ADALINE algorithms which are both parametric methods are compared in order to uncover their advantages to each other for different situations (such as different data size, closeness of harmonics in signal, etc.). Deterministic nature of Prony and stochastic approach of ADALINE to signal parameters are the most important difference between these methods. Second section of this paper summarizes basics of Prony and ADALINE algorithms. In third section, relevant simulations are realized and last section, the results are discussed.

2. METHODOLOGY

2.1. Data Model

In this study, data model is obtained from this reference (Sangwongwanich et al., 2018). This study reveals sources of inter-harmonics which are produced from Perturb and Observe Maximum Power Point Tracking (P&O MPPT) method which is implemented in photovoltaic (PV) systems. Investigated study derives mathematical expression for inter-harmonics based on realized experiments in the work. In the inspected study, it is shown that, frequency spectrum of inter-harmonics in PV systems expands if MPPT frequency is increased. Quick approximation to maximum power point with P&O MPPT causes enlargement in harmonic spectrum. Besides it is shown that amplitude of harmonics depends on step voltage which is the other parameter of P&O MPPT.

2.2. Prony Method

Prony analysis is extended form of Fourier analysis and can reveal amplitude, phase and frequency of signals. A signal can be expressed as Equation (Eq.) 1 approximately (Hauer et al. 1990). It can be observed that damping coefficient σ has important role for revealing frequency components more successfully than Fourier analysis (Xiong et al., 2010).

$$\hat{y}(t) = \sum_{i=1}^{\infty} \mathrm{A_i} e^{\sigma_i t} \cos(2\omega f_i t + \varphi_i) \tag{1}$$

If $y(t)$ is equally sampled with Δt $(y(t_k) = y(k), k = 0,1, \dots, N-1)$, strategy for obtaining solution can be summarized as below (Hauer et al. 1990).

- Step 1: Produce a linear prediction model (LPM) based on observed data.
- Step 2: Find roots of characteristic polynomial which are derived from LPM.
- Step 3: Determine complex amplitude, phase and frequency values with using roots which are determined from Step 2.

Eq. 1 can be reformed as Eq. 2.

$$\hat{y}(t) = \sum_{i=1}^{\infty} \mathrm{B_i} e^{\lambda_i t} \tag{2}$$

If sampling time expressed as t_k, the statement could be written as Eq. 3.

$$\hat{y}(k) = \sum_{i=1}^{\infty} \mathrm{B_i} z_1^k \quad , \quad z_i = e^{\lambda_i t} \tag{3}$$

In order to ensure $\hat{y}(k) = y(k)$ for all k, below equation should be solved using Eq. 3 for each t_k and $\mathrm{B_i}$ and z_i values should be determined (Hauer et al., 1990).

$$\begin{bmatrix} a_1 z_1^0 + & \dots & +a_n z_n^0 \\ a_1 z_1^1 + & \dots & +a_n z_n^1 \\ \vdots & \dots & \vdots \\ a_1 z_1^{N-1} + & \dots & +a_n z_n^{N-1} \end{bmatrix} = \begin{bmatrix} z_1^0 & z_2^0 & \dots & z_n^0 \\ z_1^1 & z_2^1 & \dots & z_n^1 \\ \vdots & & \dots & \vdots \\ z_1^{N-1} & z_2^{N-1} & \dots & z_n^{N-1} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_{N-1} \end{bmatrix} = \begin{bmatrix} y(0) \\ y(1) \\ \vdots \\ y(N-1) \end{bmatrix} \tag{4a}$$

Eq. 4a can be rewritten as Eq. 4b with matrix notation.

$$\mathbf{ZB} = \mathbf{Y} \tag{4b}$$

After finding z_i, λ_i values can be calculated with Eq. 3. All z_i are roots of a polynomial with n. degree and their coefficients can be called a_i. This can be expressed mathematically as Eq. 5.

$$z^n - (a_1 z^{n-1} + a_2 z^{n-2} + \dots + a_n z^0) = 0 \tag{5}$$

$1 \times N$ vector can be produced from Eq. 5 and expressed as Eq. 6.

$$\bar{\mathbf{A}} = [-a_n - a_{n-1} \dots -a_1\ 1\ 0 \dots 0] = [-\mathbf{a}\ 1\ \mathbf{0}] \tag{6}$$

Eq. 7 can be written with implementing Eq. 6 to Eq. 4.

$$\begin{aligned} \bar{\mathbf{A}}\mathbf{Y} &= y(n) - [a_1 y(n-1) + \dots + a_n y(0)] = \bar{\mathbf{A}}\mathbf{ZB} \\ &= B_1[z_1^n - (a_1 z_1^{n-1} + a_2 z_1^{n-2} + \dots + a_n z_1^0) + \dots] = 0 \end{aligned} \tag{7}$$

Last step in Eq. 7 is written because of providing Eq. 5 by each z_i. Comparing Eq. 5 and Eq. 7, it can be observed that Eq. 5 is general matrix equation and Eq. 7 is clearly rewritten form of Eq. 5 for each element (Hauer et al., 1990). Due to arbitrary choice of starting time, Eq. 7 can be reformed to Eq. 8.

$$\begin{bmatrix} y(n-1) & y(n-2) & \dots & y(0) \\ y(n-0) & y(n-1) & \dots & y(1) \\ \vdots & & \dots & \vdots \\ y(N-2) & y(N-3) & \dots & y(N-n-1) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_{N-1} \end{bmatrix} = \begin{bmatrix} y(n+0) \\ y(n+1) \\ \vdots \\ y(N-1) \end{bmatrix} \tag{8}$$

Solution of Eq. 8 provides coefficients of polynomial at Eq. 5. After finding roots (z_i) of the polynomial, λ_i eigenvalues could be detected. These operations complete Prony method's first and second steps. In third step, complex amplitude and phase values (B_i) are calculated (Hauer et al., 1990).

2.3. ADALINE

ADALINE is an adaptive filter which is used for feature extraction, noise suppression and different application purposes (Widrow, 1960). In recent years, this method has widely used in power quality studies. ADALINE algorithm handles Eq. 8 in stochastic manner for finding polynomial coefficients and uses frequency information which is derived from the coefficients as input in another artificial neural network (ANN) design for detecting amplitudes and phases (Chang et al., 2009). In first ANN design, past signal values are fed to input of ANN and current signal value is fed to output. Therefore, ANN coefficients are trained for polynomial coefficients of Prony method. After finding polynomial coefficients, frequency components can be calculated.

In second ANN design, found frequencies are inputs and signal values are outputs. With training second ANN, related parameters in Eq. 14 are detected. In this way, signal parameters are obtained. Frequency detection process is shown in Figure 2 and amplitude-phase finding process is shown in Figure 3.

Eq. 9 shows instant value of predicted signal with ADALINE algorithm.

$$y_f(i) = \sum_{i=1}^{k} a_m(k) y(i-m) = -\breve{a}^T(k)\,\breve{y}(i-1)$$
$$\breve{a}(k) = \begin{bmatrix} a_1(k) \\ a_2(k) \\ \vdots \\ a_M(k) \end{bmatrix} \quad , \quad \breve{y}(i-1) = \begin{bmatrix} y(i-1) \\ y(i-2) \\ \vdots \\ y(i-M) \end{bmatrix} \tag{9}$$

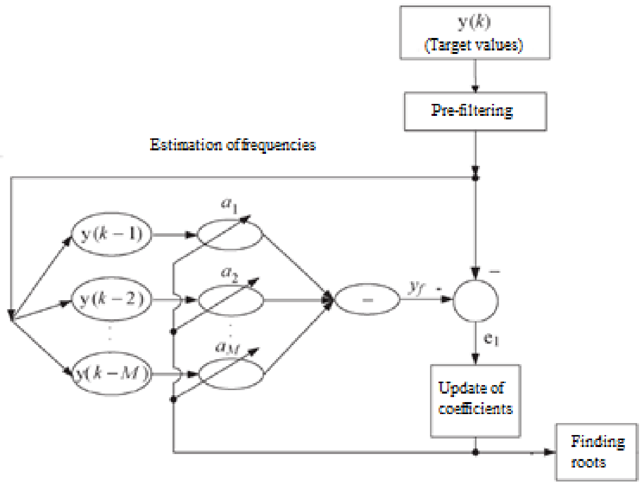

Figure 2:
Frequency estimation state of ADALINE (Chang and Chen, 2010)

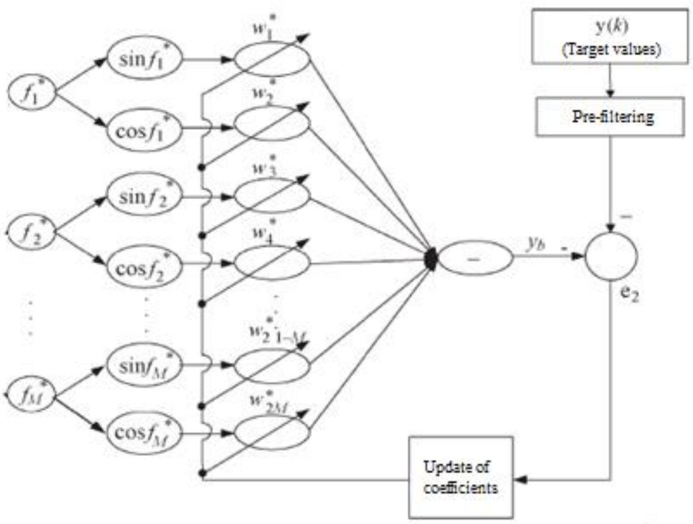

Figure 3:
Amplitude and phase estimation state of ADALINE (Chang and Chen, 2010)

Error which is occurred at system output is calculated with Eq. 10.

$$e_1(i) = y(i) - y_f(i) \tag{10}$$

$$O_1(k) = \sum_{i=1}^{k} \lambda^{k-i} e_1^2(i) \tag{11}$$

λ statement in Eq. 11 is called forgetting factor and its values between 0 and 1. It is used for weighting instant error. Neuron coefficients of ANN are updated using Eq. 12. Changes in coefficients which depend on time are calculated from Eq. 13. In this study, update mechanism of coefficients is realized with Levenberg-Marquardt unlike Eq. 13 (Levenberg, 1944; Marquardt, 1963).

$$\check{a}(k+1) = \check{a}(k) + \Delta\check{a}(k) \tag{12}$$

$$\Delta\check{a}(k) = \frac{\partial O_1(k)}{\partial \check{a}(k)} = 2\sum_{i=1}^{k} \lambda^{k-i} e_1(i)\, \check{y}(i-1) \tag{13}$$

Frequencies are obtained from $a(k)$ coefficients. Obtained frequencies are fed to ANN which is depicted in Figure 3. Output of second ANN is calculated with Eq. 14. Eq. 15 represents function to be minimized and Eq. 16 states error of ANN.

$$\begin{gathered} y_b(k) = \sum_{m=1}^{M} (A_m^* \cos\phi_m^* \sin 2\pi f_m^* k\Delta t + A_m^* \sin\phi_m^* \cos 2\pi f_m^* k\Delta t) \\ = \sum_{m=1}^{M} (w_{2m-1}^* \sin\theta_m^* + w_{2m}^* \cos\theta_m^*) = \mathrm{w}^*(\mathrm{k}).\mathrm{x}^*(\mathrm{k}) \\ \mathrm{w}^*(\mathrm{k}) = [w_1^* \quad w_2^* \quad \cdots \quad w_{2M-1}^* \quad w_{2M}^*] \\ w_{2m-1}^* = A_m^* \cos\phi_m^* \\ w_{2m}^* = A_m^* \sin\phi_m^* \\ \mathrm{x}^*(\mathrm{k}) = [\sin\theta_1^* \quad \cos\theta_1^* \quad \ldots \quad \sin\theta_M^* \quad \cos\theta_M^*] \end{gathered} \tag{14}$$

$$O_2(k) = \sum_{i=1}^{k} \lambda^{k-i} e_2^2(i) \tag{15}$$

$$e_2(i) = y(i) - y_b(i) \tag{16}$$

Eq. 17 and Eq. 18 represent update mechanism of system and are used in analyzed paper. In this study, Levenberg-Marquardt algorithm is used instead of Eq. 15 (Levenberg, 1944; Marquardt, 1963).

$$\mathrm{w}^*(k+1) = \mathrm{w}^*(k) - \Delta\mathrm{w}(\mathrm{k}) \tag{17}$$

$$\Delta w(k) = \frac{\partial O_2(k)}{\partial w(k)} = -2\sum_{i=1}^{k} \lambda^{k-i} e_2^2(i) \underline{y}(i-1) \tag{18}$$

Application steps which are used to predict polynomial coefficients by ADALINE algorithm are summarized below.

- Produce ANN (Fig. 2) with random $\breve{a}(k)$ coefficients which are also ANN coefficients.
- Find instantaneous output values according to Eq. 9.
- Update ANN coefficients with Levenberg-Marquardt algorithm until desired stop condition is satisfied (error tolerance, maximum iteration value, etc.).
- Find frequency values using Prony polynomial coefficients which are also ANN coefficients.
- Assign the frequencies to input of second ANN (Fig. 3).
- Find prediction signal with Eq. 14.
- Calculate error value with Eq. 16.
- Update second ANN using Levenberg-Marquardt until algorithm stop condition is satisfied.
- After completion of updating stage, calculate amplitude and phase values from second ANN model.

Shortly, it is seen that ADALINE comprises of two stages. In first stage, first four items are realized for finding frequencies and in second stage, last five items which are also called phase tuning steps are carried out for obtaining more approximate results to real amplitude and phase values. In this study, all steps are realized for finding frequency, amplitude and phase values and obtained result are compared with Prony method's.

3. SIMULATIONS

In this section, simulations are realized with MATLAB (MathWorks, 2019). Implemented data model is described in Methodology section. Obtained results are presented in figures and tables. In these simulations, base/fundamental/main frequency is selected as $50\ Hz$, sampling frequency is $0.5\ ms$, simulation duration is $5\ s$ ((10000) data samples).

Dataset is obtained from harmonic model of PV (Photovoltaic) system which is derived from (Sangwongwanich et al., 2018) and based on Eq. 21. In this model, step voltage and MPPT frequency have major role in creation of inter-harmonics. Step voltage causes change in amplitude of inter-harmonics while MPPT frequency affects frequency spectrum of inter-harmonics. If step voltage increases, amplitude of inter-harmonics affected positively. If MPPT frequency increases, bandwidth of inter-harmonics expands. Based on these facts, there is a trade-off between, MPPT frequency and bandwidth of inter-harmonics. First one (step voltage) is important for quick response and second one (MPPT frequency) is crucial for spectrum of inter-harmonics. On the other hand, large step voltage guarantees of quick convergence of maximum power transfer point but causes high amplitude of inter-harmonics. Therefore, there is another trade-off between step voltage and response time. In conclusion, mathematical model of inter-harmonics which are created from PV systems is given in Eq. 21. In this equation, i_g is produced current by MPPT system, f_g is fundamental (main) frequency, f_n is harmonic frequency which is created by MPPT frequency, A_n' and $\emptyset_n'$ amplitude and phase value which are affected by step voltage.

$$\begin{gathered} i_g(t) = \sum_{n=1}^{\infty} \frac{A_n}{2}\left[\cos\left(2\pi t\left(f_g - f_n\right) + \emptyset_n\right) - \cos\left(2\pi t\left(f_g + f_n\right) + \emptyset_n\right)\right] \\ a_n = \frac{2V_{step}}{\pi n}\sin\left(\frac{\pi n}{2}\right), b_n = \frac{2V_{step}}{\pi n}\cos(\pi n - 1) \\ A_n = \sqrt{a_n^2 + b_n^2}, \emptyset_n = \tan^{-1}\left(\frac{b_n}{a_n}\right), f_n = \frac{(2n-1)f_{MPPT}}{4} \end{gathered} \tag{21}$$

Three simulations are realized using Eq. 21:

1st. Step voltage is $12\,V$ and MPPT frequency is $5\,Hz$ (Table-1 and Table-2).
2nd. Step voltage is $12\,V$ and MPPT frequency is $20\,Hz$ (Table-3 and Table-4).
3rd. Step voltage is $24\,V$ and MPPT frequency is $5\,Hz$ (Table-5 and Table-6).

In second simulation, it is expected that bandwidth of inter-harmonics is wider than the first, but amplitudes of inter-harmonics are same. In third simulation, it is expected that bandwidth of inter-harmonics is same as the first, but amplitudes of inter-harmonics are higher than the first. In all simulations, Prony coefficient size is selected 80 and ADALINE neuron size is firstly selected 80 and secondly selected 800. Selection of Prony coefficient size should be equal or greater than number of harmonics in signal. Selection criteria are entirely discussed in (Rabehi et al., 2019).

In all tables it is obvious that Prony produces more successful results than ADALINE, if neuron size and coefficient size are selected same. But, when neuron size is increased, ADALINE gives better results than Prony.

In first and third simulation, signal has closer inter-harmonics than second's. Performance of Prony is weaker when inter-harmonics become closer as seen in Table-1, Table-5 and Table-3. ADALINE produces poor results when neuron size is selected 80. After neuron size is increased to 800, ADALINE gives better results (relative error converges to nearly zero) than itself and Prony as seen in Table-2, Table-4, Table-6.

In order to uncover performance of ADALINE and Prony methods under low number of data size, it would be useful to realize two more simulations. In these simulations, simulation duration is $0.1\,s$, $(200$ data samples$)$, base frequency is $50\,Hz$, sampling frequency is $0.5\,ms$, V_{step} is $12\,V$. In first, f_{MPPT} is $5\,Hz$ (Table-7 and Table-8). In second, f_{MPPT} is $20\,Hz$ (Table-9 and Table-10).

Table 1. Obtained results with Prony for MPPT simulation ($V_{step} = 12\,V, f_{MPPT} = 5\,Hz$)

Harmonic frequency (Hz)	Estimated frequency (Hz)	Relative error (%)	Harmonic amplitude (V)	Estimated amplitude (V)	Relative error (%)
38.75	38.7544	0.0114	0.8541	0.7835	8.2660
41.25	41.5980	0.8436	0.4775	0.2442	48.8586
43.75	44.0236	0.6254	1.4235	1.5974	12.2164
46.25	~	~	0.9549	~	~
48.75	48.7451	0.0101	4.2706	4.2637	0.1616
50.00	50.0203	0.0406	22	24.4907	11.3214
51.25	~	~	4.2706	~	~
53.75	52.0224	3.2141	0.9549	2.2470	135.3126
56.25	56.1521	0.1740	1.4235	1.7843	25.3460
58.75	58.6921	0.0986	0.4775	0.5463	14.4084
61.25	61.2505	0.0008	0.8541	0.8473	0.7962

Table 2. Obtained results with ADALINE for MPPT simulation ($V_{step} = 12\ V, f_{MPPT} = 5\ Hz$)

Harmonic frequency (Hz)	Estimated frequency (Hz)		Relative error (%)		Harmonic amplitude (V)	Estimated amplitude (V)		Relative error (%)	
	800 neurons	80 neurons	800 neurons	80 neurons		800 neurons	80 neurons	800 neurons	80 neurons
38.75	38.7500	39.1353	~0	0.9943	0.8541	0.8541	0.0142	~0	98.3374
41.25	41.2500	~	~0	~	0.4775	0.4775	~	~0	~
43.75	43.7500	~	~0	~	1.4235	1.4235	~	~0	~
46.25	46.2500	45.5495	~0	1.5146	0.9549	0.9549	0.0816	~0	91.4546
48.75	48.7500	~	~0	~	4.2706	4.2706	~	~0	~
50.00	50.0000	50.0166	~0	0.0332	22	22.0000	21.8280	~0	0.7818
51.25	51.2500	~	~0	~	4.2706	4.2706	~	~0	~
53.75	53.7500	~	~0	~	0.9549	0.9549	~	~0	~
56.25	56.2500	55.1083	~0	2.0297	1.4235	1.4235	0.0978	~0	93.1296
58.75	58.7500	~	~0	~	0.4775	0.4775	~	~0	~
61.25	61.2500	61.0488	~0	0.3285	0.8541	0.8541	0.0164	~0	98.0799

Table 3. Obtained results with Prony for MPPT simulation ($V_{step} = 12\ V, f_{MPPT} = 20\ Hz$)

Harmonic frequency (Hz)	Estimated frequency (Hz)	Relative error (%)	Harmonic amplitude (V)	Estimated amplitude (V)	Relative error (%)
5	5.0053	0.1060	0.8541	0.8539	0.0234
15	14.9994	0.0040	0.4775	0.4779	0.0838
25	24.9979	0.0084	1.4235	1.4241	0.0421
35	35.0033	0.0094	0.9549	0.9555	0.0628
45	44.9975	0.0056	4.2706	4.2730	0.0562
50	50.0019	0.0038	22	21.9910	0.0409
55	54.9993	0.0013	4.2706	4.2897	0.4472
65	65.0001	0.0002	0.9549	0.9544	0.0524
75	75.0000	0	1.4235	1.4309	0.5198
85	85.0000	0	0.4775	0.4768	0.1466
95	95.0000	0	0.8541	0.8558	0.1990

Table 4. Obtained results with ADALINE for MPPT simulation ($V_{step} = 12\ V, f_{MPPT} = 20\ Hz$)

Harmonic frequency (Hz)	Estimated frequency (Hz)		Relative error (%)		Harmonic amplitude (V)	Estimated amplitude (V)		Relative error (%)	
	800 neurons	80 neurons	800 neurons	80 neurons		800 neurons	80 neurons	800 neurons	80 neurons
5	5.0000	~	~0	~	0.8541	0.8541	~	~0	~
15	15.0000	~	~0	~	0.4775	0.4775	~	~0	~
25	25.0000	24.8274	~0	0.6904	1.4235	1.4235	0.2220	~0	84.4046
35	35.0000	~	~0	~	0.9549	0.9549	~	~0	~
45	45.0000	44.6511	~0	0.7753	4.2706	4.2706	0.5184	~0	87.8612
50	50.0000	50.0079	~0	0.0158	22.0000	22.0000	21.9359	~0	0.2914
55	55.0000	57.0697	~0	3.7631	4.2706	4.2706	0.1084	~0	97.4617
65	65.0000	~	~0	~	0.9549	0.9549	~	~0	~
75	75.0000	74.5606	~0	0.5859	1.4235	1.4235	0.1153	~0	91.9002
85	85.0000	84.6536	~0	0.4075	0.4775	0.4775	0.0623	~0	86.9529
95	95.0000	94.9985	~0	0.0016	0.8541	0.8541	0.8592	~0	0.5971

Table 5. Obtained results with Prony for MPPT simulation ($V_{step} = 24\,V, f_{MPPT} = 5\,Hz$)

Harmonic frequency (Hz)	Estimated frequency (Hz)	Relative error (%)	Harmonic amplitude (V)	Estimated amplitude (V)	Relative error (%)
38.75	38.7537	0.0095	1.7082	1.7166	0.4917
41.25	41.7063	1.1062	0.9549	0.3420	64.1847
43.75	44.0675	0.7257	2.8471	3.1597	10.9796
46.25	~	~	1.9099	~	~
48.75	48.8739	0.2542	8.5412	10.9924	28.6985
50.00	50.2098	0.4196	22	27.3092	24.1327
51.25	52.1878	1.8299	8.5412	2.9788	65.1243
53.75	~	~	1.9099	~	~
56.25	56.1781	0.1278	2.8471	3.4041	19.5638
58.75	58.7065	0.0740	0.9549	1.1690	22.4212
61.25	61.2503	0.0005	1.7082	1.6085	5.8366

Table 6. Obtained results with ADALINE for MPPT simulation ($V_{step} = 24\,V, f_{MPPT} = 5\,Hz$)

Harmonic frequency (Hz)	Estimated frequency (Hz)		Relative error (%)		Harmonic amplitud e (V)	Estimated amplitude (V)		Relative error (%)	
	800 neuron s	80 neuron s	800 neuron s	80 neuron s		800 neurons	80 neurons	800 neurons	80 neurons
38.75	38.7500	38.8750	~0	0.3226	1.7082	1.7082	0.8202	~0	51.9845
41.25	41.2500	~	~0	~	0.9549	0.9549	~	~0	~
43.75	43.7500	44.0438	~0	0.6715	2.8471	2.8471	0.5938	~0	79.1437
46.25	46.2500	~	~0	~	1.9099	1.9099	~	~0	~
48.75	48.7500	~	~0	~	8.5412	8.5412	~	~0	~
50.00	50.0000	49.8815	~0	0.2370	22	22.0000	11.6056	~0	47.2473
51.25	51.2500	50.8578	~0	0.7653	8.5412	8.5412	0.8474	~0	90.0787
53.75	53.7500	~	~0	~	1.9099	1.9099	~	~0	~
56.25	56.2500	56.4622	~0	0.3772	2.8471	2.8471	0.1165	~0	95.9081
58.75	58.7500	~	~0	~	0.9549	0.9549	~	~0	~
61.25	61.2500	61.2116	~0	0.0627	1.7082	1.7082	1.5284	~0	10.5257

Table 7. Obtained results with Prony for MPPT simulation ($V_{step} = 12\,V, f_{MPPT} = 5\,Hz$)

Harmonic frequency (Hz)	Estimated frequency (Hz)	Relative error (%)	Harmonic amplitude (V)	Estimated amplitude (V)	Relative error (%)
38.75	38.7982	0.1244	0.8541	0.9145	7.0718
41.25	~	~	0.4775	~	~
43.75	42.6588	2.4942	1.4235	1.4606	2.6063
46.25	~	~	0.9549	~	~
48.75	48.0929	1.3479	4.2706	0.6170	85.5524
50.00	50.2069	0.4138	22	23.0777	4.8986
51.25	~	~	4.2706	~	~
53.75	54.7418	1.8452	0.9549	2.1413	124.2434
56.25	~	~	1.4235	~	~
58.75	58.5625	0.3191	0.4775	0.5367	12.3979
61.25	61.2827	0.0534	0.8541	0.8112	5.0228

Table 8. Obtained results with ADALINE for MPPT simulation ($V_{step} = 12\ V, f_{MPPT} = 5\ Hz$)

Harmonic frequency (Hz)	Estimated frequency (Hz)	Relative error (%)	Harmonic amplitude (V)	Estimated amplitude (V)	Relative error (%)
38.75	39.7806	2.6596	0.8541	2.0346	~
41.25	~	~	0.4775	~	~
43.75	~	~	1.4235	~	~
46.25	~	~	0.9549	~	~
48.75	~	~	4.2706	~	~
50.00	50.5711	1.1422	22	26.8375	21.9886
51.25	52.0037	1.4706	4.2706	4.1420	3.0113
53.75	~	~	0.9549	~	~
56.25	~	~	1.4235	~	~
58.75	~	~	0.4775	~	~
61.25	61.9046	1.0687	0.8541	0.1627	80.9507

Table 9. Obtained results with Prony for MPPT simulation ($V_{step} = 12\ V, f_{MPPT} = 20\ Hz$)

Harmonic frequency (Hz)	Estimated frequency (Hz)	Relative error (%)	Harmonic amplitude (V)	Estimated amplitude (V)	Relative error (%)
5	~	~	0.8541	~	~
15	~	~	0.4775	~	~
25	22.6672	9.3312	1.4235	2.3468	64.8613
35	28.3178	19.0920	0.9549	0.2694	71.7876
45	44.5807	0.9318	4.2706	0.0852	98.0050
50	49.7010	0.5980	22	12.7131	42.2132
55	53.4735	2.7755	4.2706	9.8848	~
65	65.0177	0.0272	0.9549	0.9985	4.5659
75	75.0039	0.0052	1.4235	1.4204	0.2178
85	85.0001	0.0001	0.4775	0.4775	0
95	95.0000	~0	0.8541	0.8541	0

Table 10. Obtained results with ADALINE for MPPT simulation ($V_{step} = 12\ V, f_{MPPT} = 20\ Hz$)

Harmonic frequency (Hz)	Estimated frequency (Hz)	Relative error (%)	Harmonic amplitude (V)	Estimated amplitude (V)	Relative error (%)
5	~	~	0.8541	~	~
15	~	~	0.4775	~	~
25	29.6377	18.5508	1.4235	8.8180	519.4591
35	31.3281	10.4911	0.9549	7.9631	733.9198
45	48.0850	6.8556	4.2706	27.8884	553.0324
50	49.0331	1.9338	22	52.9238	140.5627
55	~	~	4.2706	~	~
65	~	~	0.9549	~	~
75	76.9587	2.6116	1.4235	2.6924	89.1394
85	81.9129	3.6319	0.4775	1.4876	211.5393
95	95.0148	0.0156	0.8541	0.4253	50.2049

In Table 7-10, it is observed that Prony method produces better results than ADALINE. Due to the fact that usage of low number of data, it could be said that ADALINE couldn't have enough data to train itself. In order to get higher efficiency for training, neuron size of ADALINE is selected 100 (This neuron size gives best performance for last simulations). In short, these simulations show that Prony produces better results for low number of data size. This makes Prony more powerful for analysis of transient response.

4. RESULTS

In this study, ADALINE and Prony methods which are both classified as parametric methods for harmonic estimation are compared. In realized simulations, data are produced from mathematical model of P&O MPPT algorithm for PV systems. This model gives opportunity to compare inspected methods under different harmonic density (closeness to each other) situations. It is difficult to be detected harmonics by Prony method as they get closer to each other. But detection performance of ADALINE method remains more stable under same conditions with Prony method.

Considering number of data size, it is observed that ADALINE method is more successful than Prony method, if its neuron size is selected relatively higher and if there is enough number of data to train ADALINE. On the other hand, Prony method gives more acceptable results for low number of data. Low number of data causes poor learning of ADALINE algorithm. It means that Prony algorithm is more reliable method for low number of data size (such as transient response of signals).

In future works, different algorithms which may also belong to distinct classes can be analyzed for revealing their advantages compared to each other in order to widening perspective of inter-harmonic estimation methods. These types of comparisons may give opportunity to design more immune algorithm for low number of data, closer harmonics and rapid changes in signals.

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