Identification and Determination of Contribution of Current Harmonics and Unbalanced in Microgrids Equipped with Advanced Metering Infrastructure

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Abstract
The use of distributed generation resources (grid-connected or islanded) such as solar systems and wind turbines in the form of microgrids can solve problems related to traditional power systems. On the other hand, the monitoring of power quality disturbances in microgrids is an important issue for compensating these problems. Among the various types of power quality disturbances, harmonic distortions are important. Accordingly, in this paper, a computational method has been used based on the recursive least squares with the variable forgetting factor (VFF-RLS). The prominent features of the proposed method are its high accuracy and speed, as well as identification with a low rate of signal samples. The main aim of the proposed method is to identify the contribution and extent of harmonics and unbalanced in a microgrid equipped with Advanced Metering Infrastructure (AMI). In the proposed method, the identification is based on real-time estimation and using measured data with high computational speed and accuracy. The results of simulation by MATLAB software, and as well as the experimental results using the TMS320F2812 digital signal processor (DSP) show the validity of the proposed method.

Keywords
Microgrid, power quality phenomena, advanced metering infrastructure, recursive least squares, identification of harmonic sources, contribution of harmonic level.

1. Introduction

Microgrids can be described as a set of different loads, energy generation sources, control equipment and a local control system that can operate both in the power grid connection, and in the island state [1 and 2]. The improvement of reliability by providing reliable power, reduction of power losses due to the low distance between the generation and consumption stations, and decreasing the environmental pollution by providing clean energy sources in microgrids are among their advantages [3]. Fig. 1 displays the structure of a power grid with several microgrids.

Microgrid control systems can be decentralized or centralized (or a combination of both). In addition, the control unit of microgrids is responsible for controlling and monitoring the important network parameters such as voltage, current, active and reactive power, etc. In this regard, Advanced Metering Infrastructure (AMI) has been presented which includes a set of smart counters, telecommunication modules, LAN, data collectors, WAN, and data management systems [4 and 5]. These systems measure the required information in the online mode and data such as voltage and current at different points, and send them to a central computing unit for processing. Identification of distortions sources and the determination of their contribution are the key issues for the microgrids connected to power systems, which is possible by AMI [6]. In implementing a smart metering system, accurate information is provided on customer consumption, as well as events and alarms, along with useful information on power quality in online mode to the central system [7]. All subscribers' information can be processed once received by the central system, where necessary commands such as disconnection or compensation are issued. Various methods have been proposed for identifying and sharing of harmonics, which are based on the computations in the frequency and time domains [8]. In [9], a general discussion has been presented on the recent notion of inverter-based distributed energy resources (IBDERs) impacts on the protection, control, operation, and planning studies of distribution networks and microgrids. To this end, different technologies of IBDERs were reviewed and then the commonly practical units were introduced. Further, in [10], a new control method has been proposed for maintaining the voltage profile in an acceptable range in the presence of the distribution generations (DGs) and under various conditions of the power system, which shows the power quality issue is very important. From the viewpoint of controlling, protection, and compensation, identification of the power quality phenomena is very significant, which can be accomplished by various identification methods. Identification methods such as Fourier series, fast Fourier transform (FFT), discrete Fourier transform, and Kalman filter are among the methods presented in the frequency domain. On the other hand, methods such as instantaneous power theory, synchronous reference frame theory, and etc. are methods based on computations in the time domain [11-12]. Among the aforementioned methods, FFT is the most common method, which has been used for identification of harmonics of a signal. FFT algorithm is a classical algorithm for harmonics detection. The harmonics components in the signal can be determined by the number of peaks in FFT spectrum. However, only the harmonic frequencies can be obtained, while the exact amplitudes of harmonics cannot be obtained from the FFT spectrum. Further, unbalanced cannot be identified by the FFT method.

Combined methods such as the wavelet transform have also been proposed based on computations in the time and frequency domain [13]. Specifications such as the speed and accuracy of identification, easy to implement, and ability to track changes in the signal components are important criteria in applying identification methods. The methods based on the frequency computations are many sophisticate, and are difficult to implement. In addition, they do not have fast response due to the delay caused by sampling for at least one power cycle as well as delay because of data transmission [14-15]. On the other hand, since frequency domain methods are mainly based on Fourier analysis, thus, they are no longer able to identify power quality phenomena such as unbalanced. Time domain methods have a lower computation volume than frequency domain methods, resulting in a higher response speed and lower response accuracy. Further, they are also easier to implement [16]. Combined methods and other computational methods such as neural networks etc. have high computational volumes. As a result, lack of rapid response and complexity of their implementation are the disadvantages of these methods [17]. Overall, a review of papers shows that the proposed identification methods suffer from the lack of fast and accurate responses. Meanwhile, simultaneous identification of the harmonics and unbalanced has not been proposed by past research. Accordingly, this paper presents a new harmonics and unbalanced identification algorithm based on recursive least squares with a variable forgetting factor. This algorithm is based on the time domain methods, and thus has a faster response and less computation. In order to enhance the accuracy of the proposed algorithm response, a variable forgetting factor is included in its structure so that it can accurately identify the harmonics under different network conditions. The proposed algorithm estimates effective harmonics with an error of about 1%, while the methods presented in [18] estimated the fifth harmonic with a 5% error. Another advantage of the proposed algorithm is simultaneous identification of harmonics and unbalanced. The need for data with low sampling rates, and as a result, easy transmission and reception of information on network parameters such as voltage and current is another advantage of the proposed algorithm. Compared to the other algorithms presented [19-20], the proposed algorithm has lower computational volume and complexity and is easy to implement. Also, the proposed algorithm is independent of the structure and parameters of the power grid and it can be used to compensate the harmonics and current unbalanced as well as applying the penalties using the information it extracts. Finally, a method has been proposed for contribution identification of each microgrid in creating the disturbances after identifying harmonics and unbalanced using the proposed algorithm. As a result, the main contributions of this paper, which introduces a new identification method, are as follows.

- Simultaneous identification of the harmonics and unbalanced of the loads' current in the presence of mixed distortions
- Fast and accurate identification of the harmonics and unbalanced of the loads' current with a low signal sampling rate
- Low complexity and easy implementation

The performance of the proposed algorithm has been illustrated by simulation using the MATLAB software as well as implementation using the TMS320F2812 digital signal processor.

The rest of this paper is organized as follows. Section 2 explains the proposed method for identification of the harmonics and unbalanced of the current. In sections 3 and 4, the simulation and experimental results have been presented for validation of the proposed method, respectively. Eventually, section 5 concludes the paper.

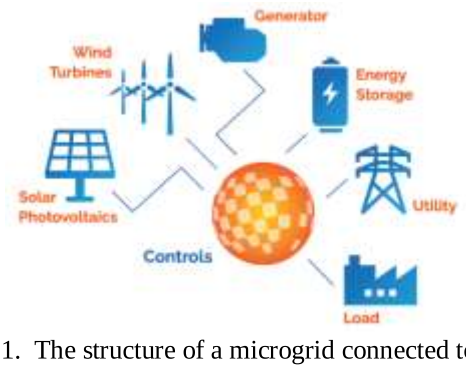


Fig. 1. The structure of a microgrid connected to the power grid

2. Proposed VFF-RLS[1] algorithm for identification and sharing

Fig. 2 depicts a diagram of a power grid with two microgrids. These microgrids include solar and wind power generation sources, energy storage, and load sources. The power generated by the solar and wind systems is injected into the DC bus. The energy is stored in the storage source

[1] Variable Forgetting Factor- Recursive Least Squares

through this bus, and the surplus is delivered through the inverter to the load and grid. Battery energy may also need to be discharged to the load and grid through the inverter. AMI systems perform online metering of important parameters of the power system, including voltage and current of the point of the common coupling (PCC) to it, at a constant sampling rate and send them to the central computing unit. Thus, at any time, the voltage and current signals of output of the microgrids and the point of common coupling of the power grid are available with the microgrids. It has been assumed that the power grid does not produce any distortions, so the power quality distortions at the PCC will be due to the microgrids. Accordingly, the proposed method identifies the harmonics and unbalanced of the current, which will be introduced in subsection 2.1.

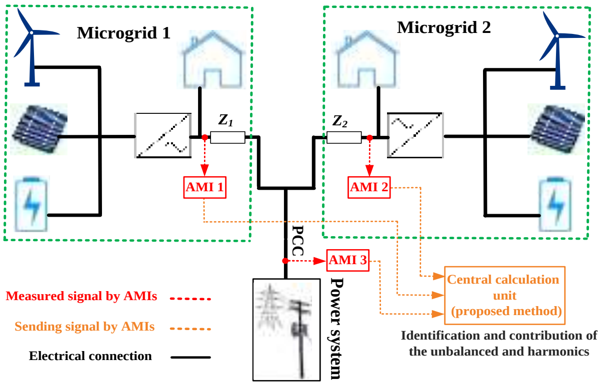


Fig. 2. The power system diagram with microgrids and AMI platform for identifying and sharing of the harmonics and unbalanced

2.1. The algorithm proposed for harmonics identification

One of the most important issues in science and engineering is signal estimation using measured signals. This is a type of estimation or filtering problem. The instrument that performs the signal estimation is called an estimator or filter. The design of an estimator can be based on the idea of the signal frequency response. If the design of an estimator is not possible based on the idea of frequency response, the advanced estimation techniques should be used, which lead to the design of the Wiener filter and recursive least squares. The recursive least squares method is a powerful mathematical tool for online estimation of the parameters of a signal. In this method, it has been assumed that the estimation has already been done up to moment t. Now the signal information received from AMI at moment t + 1 is applied and the previous estimate is modified based on the new received information. In other words, there is an instantaneous communication between the received signal and the estimator, and the estimation is updated with each new sample of received signal information. Thus, by assuming the received signal as Equation (1), this algorithm performs the estimation using Equation (2) (Estimation equation) and Equation (3) (Update Equation) [21-22].

$$y(t) = \Phi^T(\mathrm{t})\theta(\mathrm{t}) \tag{1}$$

$$\hat{\theta}(t+1) = \hat{\theta}(t) + P(t+1)\Phi(t+1)\big[y(t+1) - \Phi^T(t+1)\hat{\theta}(t)\big] \tag{2}$$

$$P(t+1) = \frac{1}{\lambda}\left[P(t) - \frac{P(t)\Phi(t+1)\Phi^T(t+1)P(t)}{1+\Phi^T(t+1)P(t)\Phi(t+1)}\right] \tag{3}$$

Where, θ represents the signal parameter matrix, $\hat{\theta}$ is the estimated signal parameter matrix, Φ^T is the signal coefficient matrix or the regressors matrix, P denotes the covariance matrix, and λ represents the forgetting factor. In the case of a sudden change in the signal parameters, the estimation error grows dramatically. In other words, under these conditions, the estimation error is higher than the estimation error of the previous step. Since the value of covariance matrix is negligible before the dramatic change of signal, and it needs to be large to correct the estimation error, thus correction of estimation error using covariance matrix is time-consuming and time response of the estimator based on RLS method is not acceptable under time-varying signal estimation.

The solution to this problem is utilization of the forgetting factor. The value of this coefficient is between minimum value and one. The minimum value is usually equal to 0.9. Using the variable forgetting factor, it can be assigned a higher weight to the estimation errors at the moment of suddenly changes in the case of unstable signal parameters, and also lower weight to estimation errors before suddenly changes. In other words, the recursive estimator forgets the initial errors. The lower value of forgetting factor leads to the faster forgetting of the initial errors. The important point is that although the forgetting factor is less than one, it improves the RLS-based time estimator response under changing signal parameters. On the other hand, after transient conditions due to signal changes and reaching a steady state, the estimation will still have error. This error can increase over time and eventually reach the limit of numerical instability. The reason for this error and its increase is that if at the moment of sudden signal changes, the value of the forgetting factor drops from one and the covariance matrix value is increased once, but the accuracy of the estimation decreases. As a result, reduction of the estimation accuracy increases the estimation error. This rise in the estimation error will in turn increase the correction interest. Thus, by increasing the covariance matrix again, the estimation accuracy falls again and the estimation error grows. This process is repeated until the estimation error increases and causes instability. To tackle this problem, a variable forgetting factor is employed. Given that at constant signal conditions, a forgetting factor of 1 is used for low estimation error, and in the conditions of changing signal parameters, this factor is momentarily reduced to less than one to achieve a fast response time (high tracking and estimation) and, after passing the transient state due to the signal changes (increasing the covariance matrix due to the changing forgetting factor), the value of the forgetting factor is increased. With low duration of variation of forgetting factor the accuracy and speed of the VFF-RLS estimator will be higher. Accordingly, parameter λ has been used in Equation (3). Parameter λ is variable with time and is expressed as Equation (4). The exponential function has been considered for λ in order to achievement fast performance.

$$\lambda(t) = \lambda_{min} + (1-\lambda_{\mathrm{min}})2^{-[\rho\alpha^2(t)]} \tag{4}$$

Where, λ_{min} is the minimum value of the forgetting factor, ρ denotes the controller for the unit area width of λ, and α represents the estimation error, expressed by (5).

$$\alpha(t) = y(t+1) - \Phi^{T}(t+1)\hat{\theta}(t) \quad (5)$$

Based on the above equations, the current signal parameters for one of the phases measured by AMI can be estimated as described below. The Equation (6) indicates the Fourier series of the current of one of the phases of the microgrids or PCC point.

$$y(t) = y_{dc} + \sum_{j=1}^{J} (\alpha_j \sin(j\omega t) + b_j \cos(j\omega t)) \quad (6)$$

According to Equation (6) and based on Equation (1), the matrix of the estimated parameters and the matrix of the regressors can be formulated as Equation (7) and (8), respectively.

$$\theta^{T}(t) = [\, y_{dc} \quad a_1 \quad b_1 \quad \dots \quad a_J \quad b_J] \quad (7)$$

$$\Phi^{T}(t) = [1 \quad \sin\omega t \quad \cos\omega t \quad \dots \quad \sin J\omega t \quad \cos J\omega t\,] \quad (8)$$

Both matrices of the Equations (7) and (8) are in rows. Equation (7) shows the fundamental component and other harmonic components of the measured current that must be estimated. Equation (8) shows the vector corresponding to each component. According to Equation (8), it can be found that all the elements of this matrix can be gained using a phase lock loop (PLL); in other words, this equation is part of the known information. Finally, by applying Equations (2) and (3), the matrix of the estimated parameters (harmonic components of the current) can be calculated for each phase of the currents received from different points of the power system. Typically, in the AC power systems, the values of the DC component and even components of the current, i.e. y_{dc} and b_j's are equal to zero. After identifying the harmonics of the current, the unbalanced components of the fundamental component can be estimated by the VFF-RLS, which is explained in subsection 2.2.

2.2. The algorithm proposed for unbalanced identification

Using the symmetric component theory, positive, negative, and zero sequences for each harmonic component extracted by the VFF-RLS, can be estimated by another VFF-RLS estimator. Thus, similar to the harmonic identification algorithm described in the previous section, the matrix of the regressors must be formulated to detect the unbalanced signal of the currents measured and transmitted by the AMIs. Equation (9) shows the relationship between components of a three-phase harmonic current and its sequences of that harmonic component.

$$\begin{bmatrix} I_0 \\ I_+ \\ I_- \end{bmatrix} = T^{-1} \begin{bmatrix} I_{ah} \\ I_{bh} \\ I_{ch} \end{bmatrix} \quad (9)$$

Where, h represents the order of the harmonic component and the T is the matrix of the symmetric sequences for the harmonic component of the h^{th}-order defined as Equation (10).

$$T = \begin{bmatrix} \sin(h\omega t) & \sin(h\omega t) & \sin(h\omega t) \\ \sin(h\omega t) & \sin(h\omega t - 120) & \sin(h\omega t + 12 \\ \sin(h\omega t) & \sin(h\omega t + 120) & \sin(h\omega t - 12 \end{bmatrix} \quad (10)$$

The elements of T matrix are known using PLL. On the other hand, the harmonic components of the current have been estimated from the previous stage; thus, using Equations (2) and (3), the symmetric sequences for each harmonic component are estimated.

The sources of harmonic and unbalanced generation in power systems have time-varying features. In other words, the amplitude of each of the harmonic components of the current and their sequences can change at any time. Methods for identifying power quality phenomena should be able to perform the identification process with good accuracy and speed, as well as under normal and abnormal conditions, and changes in the signal transmitted by AMIs. The forgetting factor λ has been taken into account in the proposed algorithm in this paper for this purpose. Indeed, this parameter gives weighted to the measured data. If the signal is in steady-state, the forgetting factor is equal to one. By this choice, according to Equations (2) and (3), the effect of the old data received from the AMIs on the identification process is greater than that of the new data; hence, the covariance matrix elements are lower and the accuracy of the proposed algorithm is high. When the signal changes, the forgetting factor is reduced to less than one. As a result, according to Equations (2) and (3), the covariance matrix values have increased, and the impact of the new data received from the AMIs on the identification process will be greater than that of the old data. Under such conditions, the accuracy of the identification is reduced for a short time and the algorithm convergence speed grows. In other words, reduction of the forgetting factor resulted in the covariance matrix reset; as a result, the convergence speed of the identification algorithm increases. Until the estimated parameters are accurately estimated, the value of forgetting factor is kept at less than one to maximize the convergence speed of the proposed algorithm. Once the estimation is done accurately, according to Equation (5), the estimation error approaches zero, and thus, according to Equation (4), the value of forgetting factor is equal to one, so that the estimation can continue with high accuracy under the new normal signal conditions. Fig. 3 reveals a block diagram of the identification of the harmonics and unbalanced by the proposed algorithm using the voltage and current signals received from the AMI.

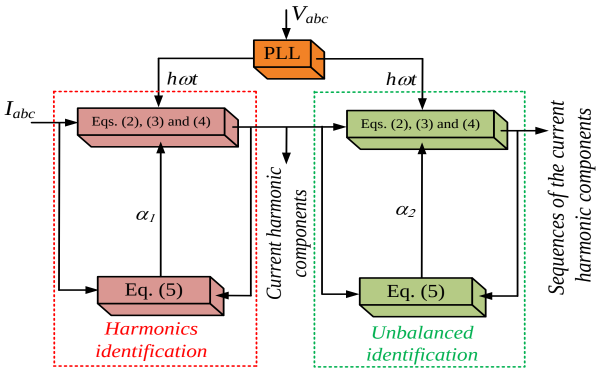


Fig. 3. The block diagram of the proposed method to identify harmonic components and current sequences

After identifying the harmonics and unbalanced of the current, the contribution of each microgrid in the production of these disturbances should be determined in the next step. A tree diagram has been proposed for this purpose in Fig. 4. Based on the results obtained from this chart, it is possible to calculate and apply any fines for each microgrid or compensation of it.

In this figure, I_{h1}, I_{h2} and I_{hpcc} represent the harmonic components of the identified current of microgrid 1, microgrid 2, and power grid at the PCC, respectively using the proposed algorithm. Similarly, I_{u1}, I_{u2} and I_{upcc} denote identified symmetric sequences of microgrid 1, microgrid 2, and power grid at the PCC by the proposed algorithm.

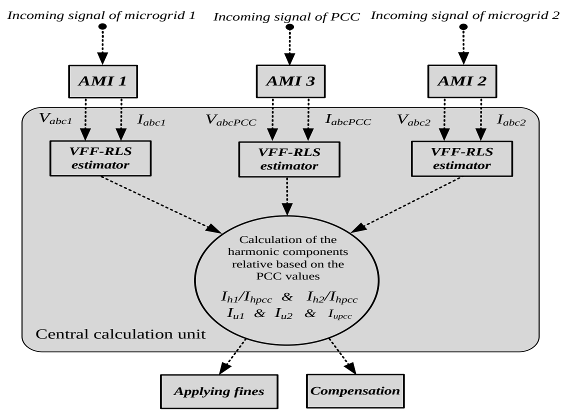


Fig. 4. The flowchart for determining the contribution of each microgrid in the PCC distortions

3. Simulation results

Fig. 5 displays the simulated power system to verify the effectiveness of the proposed algorithm. Indeed, the aim of the simulation is to evaluate the simultaneous identification of the harmonics and unbalanced of the current at the output bus of the microgrid 1 and microgrid 2, as well as the PCC bus via the proposed method.

The non-linear loads of microgrids are the main source of harmonics and unbalanced of the currents. Also, to study the accuracy and response speed of the proposed algorithm, the loads in the microgrids have been considered in both constant and time-varying states. Table I summarizes the values of the studied power system parameters. The sampling rate for the signals to detect harmonics and unbalanced is 5 kHz.

Table I. The values of the power system parameters

Parameter	Description	value
Voltage	AC voltage of power system	150 V
Frequency	Power System Frequency	60 Hz
solar system power		10 kW
Wind system power		50 kW
Constant load		4Ω, 10 Ω, 1 mH
Battery Bank Capacity		4320 AH
L_{s1} and L_{s2}	Inverter output filter	0.1 mH
R_1 and R_2	Non-linear loads resistances	0.3Ω, 0.5Ω
L_1 and L_2	Nonlinear loads inductances	0.5 mH
R_{l1} and R_{l2}	Distribution network resistances	10 μΩ
L_{l1} and L_{l2}	Distribution network inductances	1 μH
ρ_1 and ρ_2	The control coefficients of forgetting factors	4.5×10^{-5}
λ_{min}	Minimum forgetting factor	0.88

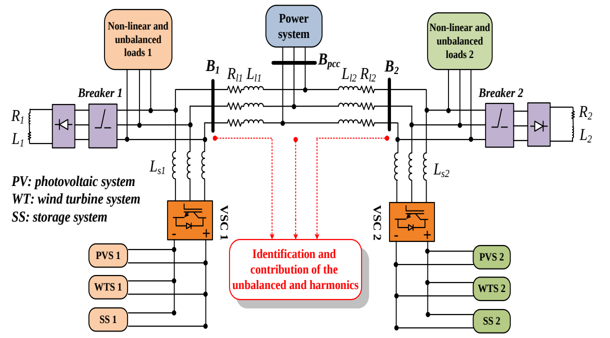


Fig. 5. The studied power system

In this power system, the circuit breakers in microgrids 1 and 2 operate at moments t = 0.6 s and t = 0.5 s, respectively, and take out the existing loads from the microgrids. Figs. 6, 7, and 8 illustrate the waveforms of the current of B_1, B_2 and B_{pcc} buses, respectively. Based on these waveforms and the circuit breakers performance, the current of bus B_1 at t = 0.6 s, bus B_2 at t = 0.5 s and bus B_{pcc} has decreased at both moments. Thus, the identification of harmonics and current unbalanced in all buses can be investigated under two operating conditions.

In the first state, there are moments where the currents are unchanged, while the second are the moments when the currents change and move from one current level to

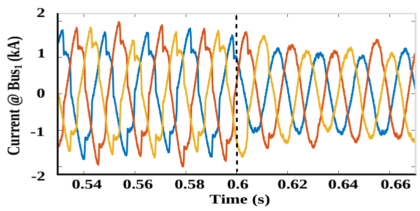


Fig. 6. B_1 Bus Current (Microgrid 1)

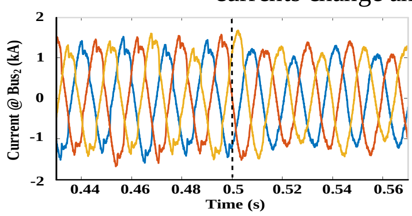


Fig. 7. B_2 Bus Current (Microgrid 2)

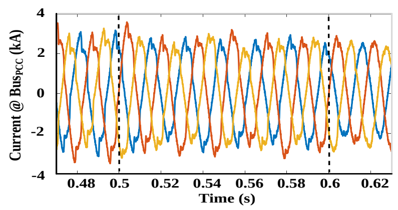
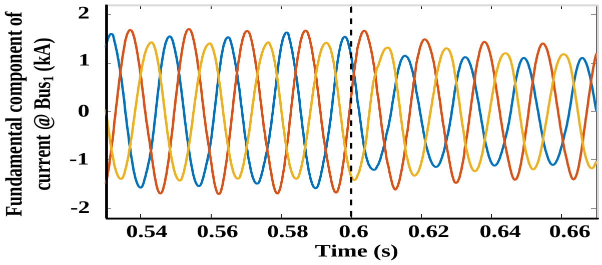


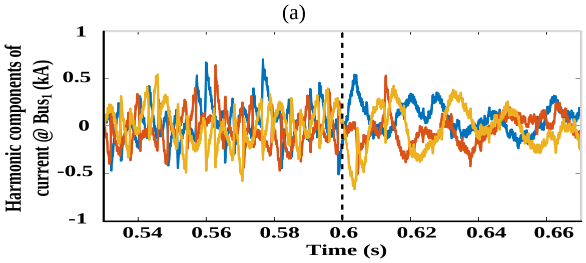
Fig. 8. B_{pcc} bus current (grid)

another. Due to non-linear and unbalanced loads, the B_1 and B_2 bus waveforms contain harmonic and unbalanced current components. The average harmonic distortion of the current of the B_1 and B_2 buses is 10% and 8%, respectively. The B_{pcc} bus current is the vector sum of the B_1 and B_2 bus currents and its average harmonic distortion is 10%.

The current waveforms of Figs. 6, 7, and 8 involve various harmonic components as well as positive, negative, and zero sequences. In order to identify the harmonic components and their unbalanced, the current of B_1, B_2 and B_{pcc} buses have been analysed by the proposed VFF-RLS estimator. The waveforms in Figs. 9 (a), (b), (c) and (d) represent the fundamental component of the current, harmonic content of the current, positive sequence of the fundamental component, and negative sequence of the bus B_1, respectively.



(a)



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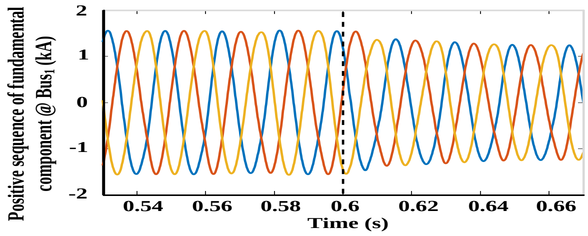
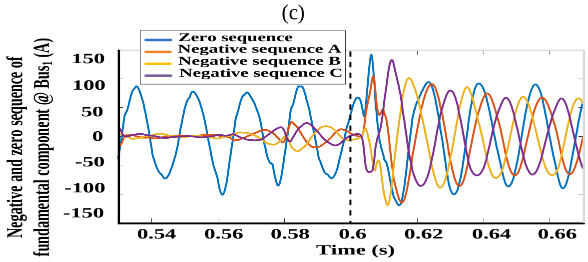


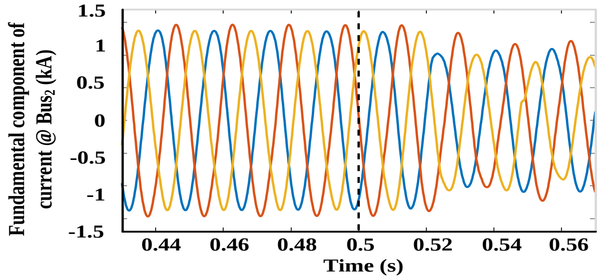
(c)



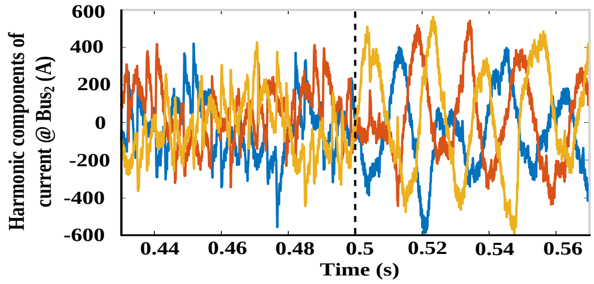
(d)

Fig. 9. The B_1 bus current analysis of (a) the fundamental component of the current, (b) the harmonic components of the current, (c) the positive sequence of the fundamental current component, and (d) the negative and zero sequences of the fundamental current component.

Similar to B_1 bus, the current signal has been analysed using VFF-RLS estimator for B_2 and B_{pcc} buses. The parameters of the current fundamental component, harmonic components, the current positive sequence of the fundamental component, as well as the negative and zero sequences of the fundamental current component have been estimated, in Figs. 10 (a), (b), (c) and (d) and for bus B_2 and Figs. 11 (a), (b), (c) and (d) respectively for B_{pcc} bus.



(a)



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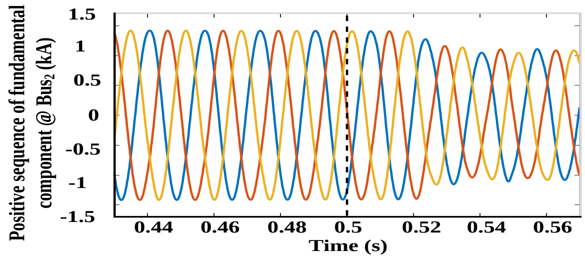
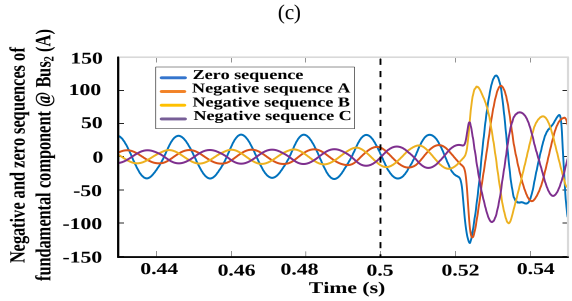


(c)



(d)

Fig. 10. The current analysis of B_2 bus (a) fundamental current component, (b) harmonic components of the current, (c) positive sequence of the current fundamental component, and (d) negative and zero sequences of the fundamental current

Figs. 9, 10, and 11 demonstrate the current analysis results of B_1, B_2 and B_{pcc} buses. The fundamental current components, harmonic components, and current sequences with high speed and accuracy were identified by the VFF-RLS estimator. The proposed estimator uses a variable forgetting factor to increase the accuracy and speed of estimation by resetting the covariance matrix. For this purpose, when the signal parameters such as harmonic components or sequences change over time, the forgetting factor is reduced to less than one and the covariance matrix is reset. By resetting the covariance matrix, the new received data of the signal play a more significant role in estimating the signal parameters than the previous received data. Thus, the estimation accuracy diminishes for a short time while the estimation speed increases until the estimation parameters are accurately identified and the forgetting factor increases to one. Fig. 12 (a) and (b) indicate the changes in the forgetting factor and the covariance matrix for estimating the fundamental component of the B_{pcc} bus current.

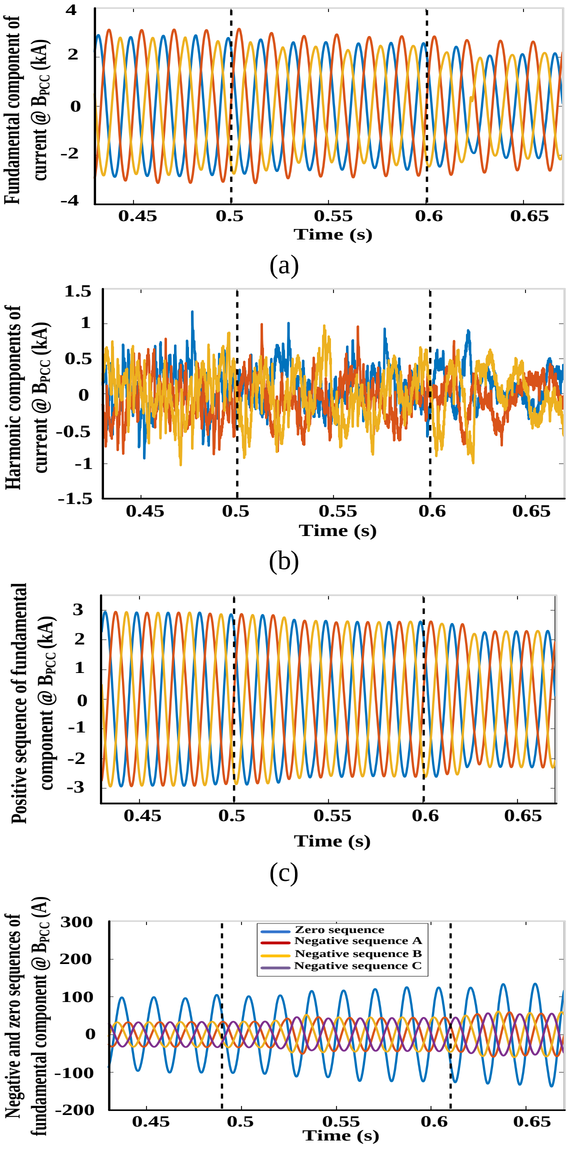


Fig. 11. The current analysis of B_{pcc} bus (a) fundamental current component, (b) harmonic components of current, (c) positive sequence of the current fundamental component, and (d) negative and zero sequences of the fundamental current.

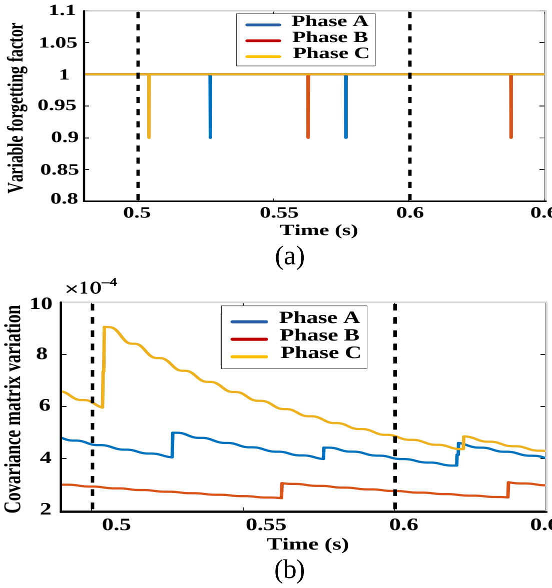


Fig. 12. The changes in (a) forgetting factor and (b) covariance matrix to estimate the fundamental component of B_{pcc} bus current.

According to Fig. 12(a), after the moment of changes in the received current signal, t = 0.5 s and t = 0.6 s, the values of the forgetting factor for each phase of the current decrease to less than 1. Simultaneously with this operation and according to Equation (3), the covariance matrix corresponding to each phase of the current is reset.

This is illustrated in Fig. 12 (b). According to Fig. 12 (a) and (b), the covariance matrix has been reset with variations in the forgetting factor in Fig. 12 (a) and (b). In phase A, the forgetting factor has been changed twice. The reason is that when the forgetting factor changes for this phase, the estimated parameter is not sufficiently accurate and the algorithm has decreased again the forgetting factor. However, the identification process has been performed with high accuracy and speed for phase C with one time of decreasing in the forgetting factor and hence the reset of the covariance matrix. The identification results indicate that the harmonic and unbalanced identification by the proposed method has been performed in less than one power cycle and with great accuracy. Similar to the estimation of the fundamental components of the B_{pcc} bus current, the proposed estimator for identifying the positive and negative sequences of the fundamental component of this bus has changed the forgetting factor and led to enhanced convergence of the parameter estimation by resetting the covariance matrix. The B_1 and B_2 bus currents are similar to the B_{pcc} bus current with the proposed estimator, where the fundamental current components, harmonic components, and symmetric sequences of the harmonic components are also identified. Considering the volume of the results of the figures and the similarity of the analysis of the bus currents, the results of the simulations of identifying the harmonics and the unbalanced of the bus currents under conditions often associated with microgrids have been summarized in Table II.

Table II summarizes the results of the estimation and identification of the harmonic components of the fundamental, third, fifth, seventh, and ninth order-harmonics as well as the symmetric sequences of each harmonic component using the proposed algorithm. The results have had very good accuracy, and using them it can be determined the contribution of each microgrid to a large extent in producing harmonic disturbances. For example, for the seventh harmonics identified in Phase A of B_{pcc} bus, the first microgrid has 65% share and the second microgrid has 29%. Due to the phase difference between the current components and the identification error, the sum of the contamination percentages of the microgrids may not necessarily be 100%. Table 3 reports the percentage of each microgrid of the B_{pcc} bus harmonics generation and the estimation error. The results can be used to apply penalty and to compensate for distortions.

Table II. Identification of harmonic and unbalanced components of bus current

Amplitude of the harmonic components (A)	B_1			B_2			B_{pcc}		
Fundamental	A	B	C	A	B	C	A	B	C
	1690	1520	1550	1460	1330	1310	3200	2900	2950
	P*	N**	Z***	P	N	Z	P	N	Z
	1585	24	59	1337	15	31	3043	29	104
Third	A	B	C	A	B	C	A	B	C
	13	9.5	19	4.5	5	10	18	15	30
	P	N	Z	P	N	Z	P	N	Z
	17	1	3	17	1	3	18	15	13
Fifth	A	B	C	A	B	C	A	B	C
	33	135	94	41	77	33	75	210	125
	P	N	Z	P	N	Z	P	N	Z
	14	55	71	9.5	26	40	3	59	100
Seventh	A	B	C	A	B	C	A	B	C
	79	80	76	36	37	35	118	123	115
	P	N	Z	P	N	Z	P	N	Z
	78	3.2	1.5	41	0.7	0.7	122	1	4
Ninth	A	B	C	A	B	C	A	B	C
	1	1.5	2	1.05	0.9	1.9	2	2.5	4
	P	N	Z	P	N	Z	P	N	Z
	4	0.6	0.5	2.5	2.2	1.2	7	0.8	1.5

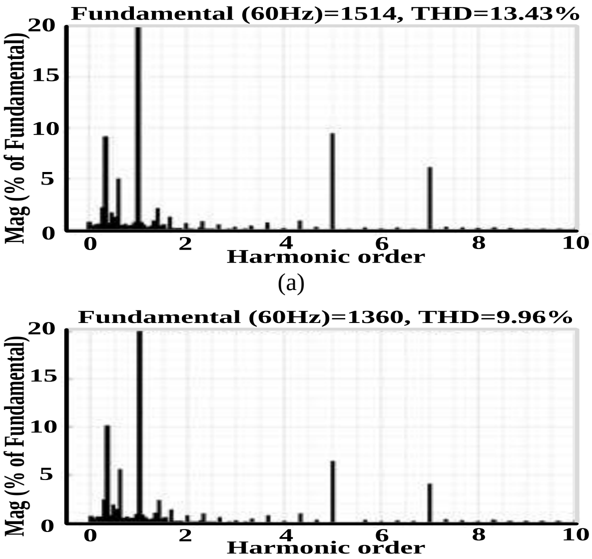
*Positive, **Negative, ***Zero

Table III. Percentage of share of harmonic generation and its estimation error

		Harmonic order				
	Phase	Fundamental	Third	Fifth	Seventh	Ninth
Contribution of microgrid 1 (%)	A	%52.8	%72.2	%44	%66.9	%50
	B	%52.4	%63.3	%64.2	%65	%60
	C	%52.5	%63.3	%75.2	%66.1	%60
Contribution of microgrid 2 (%)	A	%45.6	%25	%54.7	%30.5	%52.5
	B	%45.8	%33.4	%36.7	%30.1	%36
	C	%44.4	%33.3	%26.4	%30.4	%47.5
Accuracy of the stimation at B_{pcc} (%)	A	%1.5	%2.7	%1.3	%2.5	%-2.5
	B	%1.7	%3.3	%-0.9	%0.8	%4
	C	%3	%3.3	%-1.6	%-3.4	%2.5

There are some important points in Table III. The first is about the fundamental component of the current.

On average, 52% of this component is absorbed by microgrid 1 and 45% by microgrid 2. The remaining 5% is supplied by generation energy sources (assuming inverters inject the fundamental component current into the grid). The next point is the good accuracy of identifying the first, fifth, and seventh components. These harmonic components have been identified with good accuracy, while the third and ninth harmonic components have less accuracy than the first, third, and fifth components. The reason is that in examining the harmonic spectra of the bus currents, it is found that the fifth and seventh harmonic components have high amplitude while the amplitudes of the third and ninth harmonic components are very low.



(a)

(b)

Fig. 13. Harmonic spectrum of buses (a) Microgrid 1 and (b) Microgrid 2

The last point in Table III is the estimated error rate of the harmonics. The values for this column have been obtained by comparing the estimated values with the actual values of the harmonic components. Indeed, the estimated error values of the harmonics represent the actual estimated error rate. Fig. 13 (a) and (b) show the harmonic spectrum of the current of microgrids 1 and 2 buses, respectively. Meanwhile, the estimation accuracy can be improved by properly adjusting the unit area coefficient of the proposed estimation method. Also, by increasing the sampling frequency from the current signal, the identification accuracy of the harmonic components of the current can be enhanced. Thus, the proposed algorithm is highly accurate in identifying the harmonic components which on average detects effective harmonics with an error of about 2%. The comparison between the proposed method and other methods has been made in Table IV. Note that this comparison has been accomplished considering identification of the harmonics of the current. According to this table, the proposed method has greater identification accuracy than the previous methods. Based on Table IV, the proposed identification method can identify harmonics with high accuracy, in spite of the low sampling frequency. Further, the proposed method can identify the harmonics of the current in the presence of mixed distortions. The performance of the proposed method under mixed distortions has been outlined in Table V. The speed of the proposed method for estimating under transient conditions (i.e., when there is a change in the estimated parameters) is high and is about one power cycle. However, in previous methods, the parameter estimation speed has been far higher. The reason for the rapid response of the estimation method is that this method is based on recursive calculations where estimating parameters calculations are performed for each measured sample. In addition, the use of the variable forgetting factor method indicates this fact that by resetting the covariance matrix under transient conditions, new data have a greater impact on the estimation process than older data, thus increasing the speed of estimation. Note that in the simulations, the sampling frequency has been set at 5 kHz, which grows with the sampling rate, while the estimation speed is lower than a power cycle.

Table IV. The comparison between the proposed method and previous methods

Reference number	method	Identification accuracy	Sampling frequency (kHz)
[18]	IM	95%	10
[23]	SVM	89.4%	10
[24]	KNN	90.5%	12.5
[25]	ICA	94.1%	12.8
proposed	VFF-RLS	98%	5

Table V. The performance of the proposed method in the presence of mixed distortions

Mixed distortions	Accuracy of estimation (%)
Harmonic + transient	93.6
Harmonic + sag	98
Harmonic + swell	98
Harmonic + Frequency oscillation	95.3

4. Experimental results

A laboratory-scale power system has been implemented to prove the efficiency of the proposed method and the simulation results. Fig. 14. depicts a schematic of the power system under study.

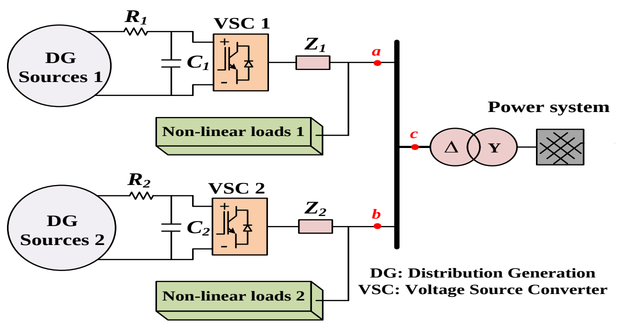
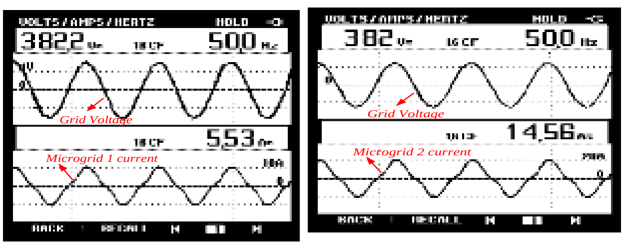


Fig. 14. The schematics of the laboratory power system

Based on Fig. 14, R_1, C_1 and R_2, C_2 are values related to the DC resistance and capacitance of the microgrids, while the Z_1 and Z_2 are the output impedance of the microgrids.



(a) (b)

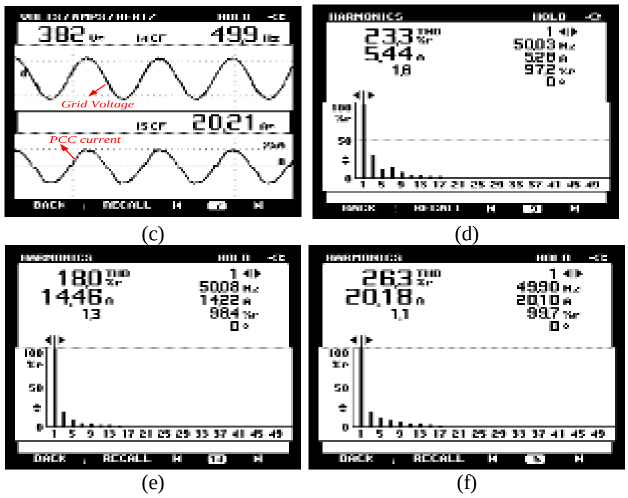


Fig. 15. The voltage and current waveforms of the (a) microgrid 1, (b) microgrid 2 and (c) power system input or PCC bus

The harmonic spectrum of the current at the specified points a, b, and c are respectively corresponding to the output bus of microgrids 1, 2 and the bus connecting to the power grid i.e. B_{pcc} has been measured by a power analyser. Fig. 15 (a)-(f) depict the measurements performed. According to this figure, microgrid 1 generated a THD contamination rate of 23.3% and microgrid 2 produced a THD contamination rate of 18%. Accordingly, the THD contamination rate in the common bus with the power system is 26.3%. In order to prove the efficiency of the proposed method, an approximate VFF-RLS based method is implemented on the digital signal processor (DSP) TMS320F2812. Further, the current signal of the common bus of the power system (B_{pcc}) is applied to the analogue input of this processor and evaluated by the proposed method, with the results presented in Table VI.

Table VI. The estimates of B_{pcc} common bus current harmonics

Harmonic order	Measurement values	Estimation values
Fundamental	20.1	20.8
Third	4.01	3.82
Fifth	2.02	1.98
Seventh	1.32	1.2
Ninth	1.1	1.03
Eleventh	0.9	0.88
Thirteen	0.62	0.65
Fifteen	0.43	0.42
Seventeen	0.24	0.22

Table VI provides the values measured by the power analyser Fluke 43B. On the other hand, the estimated values were calculated using the proposed method on DSP model TMS320F2812. Comparison of the results shows that the estimation method has been very accurate in estimating the harmonic components of the current in the common bus of the power system. For the sake of simplicity, Fig. 16 demonstrates the bar diagram of the values of Table VI. As can be seen from this figure, the results of the proposed method, obtained based on the TMS320F2812 DSP, have high accuracy.

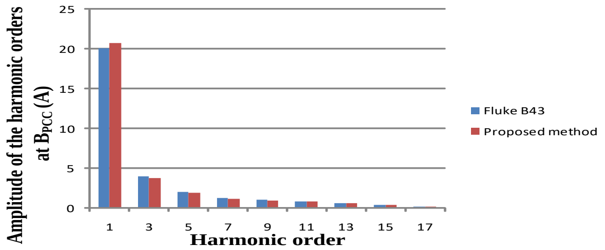


Fig. 16. The results of the experimentation

5. Conclusion

This paper presented a new algorithm for identifying and estimating of the harmonics and unbalanced current distortions based on recursive least squares method with a variable forgetting factor. In order to validate the proposed algorithm, a power system consisting of two microgrids with nonlinear and unbalanced loads connected to the power grid was simulated. The proposed method was also implemented on a TMS320F2812 digital signal processor. The analysis of the signals received from the microgrid buses and the power grid bus by the proposed algorithm determined the extent of harmonic and unbalanced distortions of their currents. The results indicate that the proposed algorithm has a higher accuracy and computational speed than previous methods with a lower signal sampling rate. Finally, the results of the identification of the harmonic sources were used to determine the contribution of each microgrid to the harmonic pollution in the power grid bus.

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